ANL/ESD-14/4
Revision 1

Light-Duty Vehicle Fuel Consumption Displacement Potential up to 2045

Energy Systems Division

U.S. DEPARTMENT OF ENERGY

Energy Efficiency & Renewable Energy

About Argonne National Laboratory
Argonne is a U.S. Department of Energy laboratory managed by UChicago Argonne, LLC under contract DE-AC02-06CH11357. The Laboratory's main facility is outside Chicago, at 9700 South Cass Avenue, Argonne, Illinois 60439. For information about Argonne and its pioneering science and technology programs, see www.anl.gov.

ANL/ESD-14/4
Revision 1

Light-Duty Vehicle Fuel Consumption Displacement Potential up to 2045

prepared by
Ayman Moawad and Aymeric Rousseau
Energy Systems Division, Argonne National Laboratory

April 2016

CONTENTS

FIGURES

TABLES

ACKNOWLEDGMENTS

This study was supported by the U.S. Department of Energy (DOE) FreedomCAR Program and Vehicle Technology Office under the direction of David Anderson and Lee Slezak.

ABOUT THE AUTHORS

Aymeric Rousseau is the manager of the Vehicle Modeling and Simulation Section at Argonne National Laboratory. He received his engineering diploma at the Industrial System Engineering School in La Rochelle, France, in 1997. After working for PSA Peugeot Citroen in the Hybrid Electric Vehicle research department, he joined Argonne in 1999, where he is responsible for the development of Autonomie. He received an R&D 100 Award in 2004 and a Vehicle Technologies Program R&D Award in 2010. He has authored more than 40 technical papers in the area of advanced vehicle technologies.

Ayman Moawad is a research engineer in the Vehicle Modeling and Simulation Section at Argonne National Laboratory. He graduated from the Ecole des Mines, France, in 2009, with a Master's Degree in Science, majoring in Automatics, Control Systems, and Industrial Computer Science. His research focuses on light-duty vehicle fuel-consumption analysis as well as powertrain costs to support the Government Performance and Results Act.

NOTATION

ACRONYMS AND ABBREVIATIONS

AER	all-electric range
Argonne	Argonne National Laboratory
APRF	Advanced Powertrain Research Facility
BEV	battery-powered electric vehicle
BOL	beginning-of-life
CAFE	Corporate Average Fuel Economy
CD	charge depleting
CI	compression ignition
CNG	compressed natural gas
CO_2	carbon dioxide
CS	charge sustaining
CSI	Civil Society Institute
DCT	dual-clutch transmission
DOE	U.S. Department of Energy
E85	blend of 85% ethanol and 15% gasoline by weight
EDV	electric drive vehicle
EIA	Energy Information Administration
EOL	end of life
EPA	U.S. Environmental Protection Agency
E-REV	extended-range EV
EVS	International Electric Vehicle Symposium
GDI	gasoline direct injection
GHG	greenhouse gas
GPRA	Government Performance and Results Act
GVW	gross vehicle weight
HEV	hybrid electric vehicle
HWFET	Highway Federal Emissions Test
ICE	internal combustion engine
IEA	International Energy Agency
IVM	initial vehicle movement

Li-ion	lithium ion
MPGGE	miles per gallon gasoline equivalent
MY	model year
NEMS	National Energy Modeling System
NiMH	nickel metal hydride
OEM	original equipment manufacturer
PHEV	plug-in hybrid electric vehicle
PHEV 10 and 20	PHEV with 10 or 20 miles of all-electric range
PHEV 30 and 40	PHEV with 30 or 40 miles of all-electric range
PSAT	Powertrain System Analysis Toolkit
P/W	power to weight ratio
R&D	research and development
SAE	Society of Automotive Engineers
SI	spark ignition
SOC	state of charge
SUV	sport utility vehicle
UDDS	Urban Dynamometer Driving Schedule
UF	utility factor
US06	duty cycle with aggressive highway driving
VCR	variable compression ratio
VTP	Vehicle Technologies Program
VTS	Vehicle Technical Specifications
VVT	variable valve timing

UNITS OF MEASURE

A	ampere(s)
Ah	ampere-hour(s)
bbl	barrel(s)
°C	degree(s) Celsius
°F	degree(s) Fahrenheit

gal	gallon(s)
h	hour(s)
kg	kilogram(s)
km	kilometer(s)
kW	kilowatt(s)
L	liter(s)
lb	pound(s)
m	meter(s)
m^2	square meter(s)
mi	mile(s)
mpg	mile(s) per gallon
mph	mile(s) per hour
MW	megawatt(s)
sec	second(s)
V	volt(s
Wh	watt hour(s)

ABSTRACT

The U.S. Department of Energy (DOE) Vehicle Technologies Program (VTP) is developing more energy-efficient and environmentally friendly highway transportation technologies that will enable America to use less petroleum. The long-term aim is to develop "leapfrog" technologies that will provide Americans with greater freedom of mobility and energy security, while lowering costs and reducing impacts on the environment. DOE's VTP examines pre-competitive, high-risk research needed to develop:

- Component and infrastructure technologies necessary to enable a full range of affordable cars and light trucks.
- Fueling infrastructure to reduce the dependence of the nation's personal transportation system on imported oil and minimize harmful vehicle emissions, without sacrificing freedom of mobility and freedom of vehicle choice.

As part of this ambitious program, numerous technologies, such as the following, are addressed: engines, energy storage systems, fuel-cell systems, hydrogen storage, electric machines, and materials.

The 1993 Government Performance and Results Act (GPRA) holds federal agencies accountable for using resources wisely and achieving program results. GPRA requires agencies to develop plans for what they intend to accomplish, to measure how well they are doing, to make appropriate decisions on the basis of the information they have gathered, and to communicate information about their performance to Congress and to the public. The present study evaluates the benefits of the light-duty vehicle research conducted at DOE from fuel-efficiency and cost perspectives, to support GPRA activities.

Because of the large number of component and powertrain technologies considered, the benefits were simulated using Autonomie. Argonne National Laboratory designed Autonomie to serve as a single tool that can be used to meet the requirements of automotive engineering throughout the development process, from modeling to control. Autonomie, a forward-looking model developed using MathWorks tools, offers the ability to quickly compare powertrain configurations and component technologies from the perspective of performance and fuel-efficiency.

This report reviews the results of the DOE VTP. It gives an assessment of the fuel and light-duty vehicle technologies that are most likely to be established, developed, and eventually commercialized during the next 35 years (up to 2045). Because of the rapid evolution of component technologies, this study is performed on a yearly basis to continuously update the results based on the latest state-of-the-art technologies.

While it is not possible to simulate all the different combinations, more than 2,000 vehicles were simulated in the study to take the following into account:

- Major powertrain configurations (i.e., conventional, power-split, extended-range electric vehicle (E-REV) and battery electric drive),
- Major vehicle classes (i.e., compact car, midsize car, small sport utility vehicle [SUV], large SUV, and pickup), and
- Major fuels (i.e., gasoline, diesel, compressed natural gas (CNG), and ethanol).

These technologies were assessed for five different timeframes—2013, 2015, 2020, 2030, and 2045. Finally, uncertainties were included for both performance and cost aspects by considering three cases:

- Low case (10% uncertainty) — aligned with original-equipment-manufacturer improvements based on regulations,
- Average case (50% uncertainty), and
- High case (90% uncertainty) — aligned with aggressive technology advancement based on DOE’s VTP.

The objective of the report is to provide an assessment of the conventional-fuel displacement and cost-reduction potentials of advanced technologies up to the year 2045, including uncertainties.

EXECUTIVE SUMMARY

The U.S. Department of Energy (DOE) Vehicle Technologies Program (VTP) supports new technologies to increase energy security in the transportation sector at a critical time for global petroleum supply, demand, and pricing. Consequences of our vehicles' dependence on oil as their source of energy were shown by the "first oil shock" brought on by the petroleum embargo of October 1973 and the "second oil shock" of 1979. However, this oil dependence continues to increase unabated to the present, and the oil price run-up of July 2008 ($147 per barrel of crude) illustrated the rapidity with which these discontinuities can occur. As such, the lack of widely available and viable alternative non-petroleum-based fueling options for ground transport vehicles constitutes a high risk to stable economic activity. Some means of providing energy to move vehicles that greatly reduces or eliminates petroleum consumption must be developed. This challenge is greatly complicated by the fact that virtually all alternatives have some inherent fossil-fuel component. The U.S. transportation sector used about 13.1 million barrels of oil equivalent per day in 2011. It consumed more oil than the total U.S. domestic oil production. On-highway vehicles (passenger and commercial vehicles) used more than 11.2 million barrels of oil equivalent per day, which accounts for more than 85% of the total transportation oil use and over 59% of total U.S. oil use. The VTP focuses on ground transportation vehicles because of their dominant contribution to the nation's oil use.

The VTP collaborates with industry to identify priority areas of research needed to develop advanced vehicle technologies to reduce and eventually eliminate petroleum use, and to reduce emissions of greenhouse gases (GHGs), primarily carbon dioxide (CO_2), from carbon-based fuels. The VTP works on numerous technologies, including the following:

- Development of hybrid electric vehicles (HEVs) and plug-in HEVs (PHEVs), which can significantly improve fuel economy and petroleum displacement. This research supports President Obama's goal of 1 million PHEVs and EVs by 2015.
- Deployment of alternative fuels, which can rapidly reduce oil imports.
- Reduction of vehicle weight directly improves vehicle efficiency and fuel economy and can potentially reduce vehicle operating costs.
- Improved combustion technologies and optimized fuel systems can improve near- and mid-term fuel economy for passenger vehicles by 25% to 40% for passenger vehicles by 2015.

The objective of the present study is to evaluate the benefits of the DOE VTP for a wide range of vehicle applications, powertrain configurations, and component technologies for different timeframes, and to quantify the potential future petroleum displacement up to 2045, as well as the cost evolution. More than 2,000 light-duty vehicles were simulated with Autonomie, Argonne National Laboratory's (Argonne's) vehicle simulation tool.

Because of the large number of powertrain and component technologies, only a limited number of combinations were taken into account (i.e., micro or “mild” HEVs were not included), leading to the consideration of more than 2,000 vehicles. To address performance and cost uncertainties, three cases were considered: low (10%), average (50%), and high (90%) uncertainty. When available, the high-case assumptions were based on the FreedomCAR and Fuel Partnership program goals. The other assumptions were developed through discussions with experts from companies, universities, and the national laboratories. While the uncertainties are expected to provide a range, it should be noted that several ongoing research projects or lack of data for specific technologies could lead to significantly higher fuel-efficiency gains than considered in the study. For example, the engine gains could be considered less aggressive than for other technologies, and readers should take this parameter into account during the analysis. More than 400 assumptions were necessary to define each vehicle. Some of the main assumptions are highlighted below:

- The difference in peak efficiency between gasoline and diesel engines is expected to narrow in the future because of the combination of advanced gasoline engine technologies and the impact of evermore stringent after-treatment for diesel.
- Coupling ultra-capacitors with batteries was not considered, owing to higher cost and expected increase in lithium ion (Li-ion) battery life and cold-start performance in the short term.
- Because of the drive quality requirements in North America, automated manual transmissions were not included in the study. Continuously variable transmissions (CVTs) have also shown issues with reliability and fuel-efficiency gains and were not considered.
- The peak efficiencies of fuel-cell systems remain constant in the future, as most research is expected to focus on reducing cost and increasing durability. The costs used were based on the assumption that 500,000 units are produced per year.

The main results related to vehicle sizing, fuel efficiency, and cost are highlighted in the following sections.

ES.1. VEHICLE SIZING

Advances in material substitution will play a significant role in reducing overall vehicle weight and, consequently, component power and energy requirements.

- Because of the impact of the component max-torque shapes, maintaining a constant power-to-weight (P/W) ratio between all configurations leads to an inconsistent comparison between technologies due to different performances. Each vehicle should be sized independently to meet specific Vehicle Technical Specifications (VTS).

- Reducing the vehicle weight ("lightweighting") has greater influence on electric drive vehicles (EDVs) than on their conventional counterparts due to the impact of the battery mass on EVs.
- While performance (i.e., time for 0–60 mph) is the primary factor used to size components for current technologies, aggressive future lightweighting can make gradeability requirements the critical sizing criteria.
- Vehicle weight decreases in the range of 12% to 65% by 2045 across powertrain configurations. The weight reduction, however, varies with the configuration. For the configurations using an engine, the weight reduction for the gasoline conventional powertrain ranges from 12% to 40%, power-split HEVs from 15% to 43%, low-energy PHEVs (with all-electric ranges, or AERs, of 10 and 20 mi) from 16% to 45%, and high energy PHEVs (30- and 40-mi AERs) from 20% to 48%. Configurations with fuel-cell systems demonstrate a larger weight reduction, with fuel-cell HEV weight reductions ranging from 25% to 54%, low-energy PHEV10s and PHEV20s (i.e., 10- and 20-mi AERs) from 25% to 55%, and high-energy PHEV30s and PHEV40s (30- and 40-mi AERs) from 29% to 58%. Finally, battery-powered electric vehicles (BEVs) achieve a weight reduction ranging from 25% to 65%. Overall, significant weight reductions can be achieved compared with current technologies, especially for vehicles with large batteries.
- Most of the component peak powers show a strong linear correlation with vehicle weight. As a result, it is necessary to include secondary effects when analyzing the lightweighting benefits.
- Because of lightweighting and component efficiency improvements, the peak power of engine and fuel-cell systems could be significantly reduced over time to meet current VTS. Engine peak power could be reduced by 2045 over a 16% to 33% range for conventional gasoline, 17% to 43% for gasoline power-split HEVs, and 18% to 44% for low-energy and high-energy PHEVs. As seen for vehicle weight, hydrogen-fueled vehicles demonstrate a larger peak-power improvement than gasoline-fueled vehicles over time, with fuel-cell system power decreasing in the range of 22% to 48% for HEVs, 23% to 49% for low-energy PHEVs, and 25% to 51% for high-energy PHEVs.
- Battery peak power is also expected to decrease over time to meet current vehicle performance. The battery power is expected to decrease up to 50% for gasoline-engine HEVs and PHEVs.
- Battery total energy will be decreasing significantly owing to other component improvements, as well as a wider usable state of charge (SOC) range. The reduction in energy required for PHEVs and BEVs could range from 37% to 64% by 2045.
- While the fuel selection influences the engine size for conventional vehicles (i.e., diesel has lower peak power than gasoline to higher maximum torque at low speed), the power required to meet the VTS for EDVs is comparable across all fuels.

The different PHEVs show a linear relationship between the usable battery energy and the vehicle mass, with the slope increasing with the AER.

ES.2. VEHICLE FUEL-EFFICIENCY

Overall, the combination of technology improvements leads to significant fuel-consumption reduction across vehicle applications. As a result, significant fuel can be displaced over the next few decades. There is a linear relationship between lightweighting and fuel and electrical consumption. However, as previously discussed, that relationship differs depending on the powertrain configuration.

ES.2.1. EVOLUTION OF FUEL CONSUMPTION COMPARED WITH REFERENCE 2013 GASOLINE CONVENTIONAL VEHICLE

Table ES-1 shows the adjusted fuel-consumption reduction by 2045, on the combined driving cycle, for each powertrain configuration and fuel, compared with the reference gasoline conventional vehicle.

The results demonstrate significant improvements over time across all powertrain configurations and fuels (Table ES-1). When considering the high-uncertainty case across all engines, conventional vehicles can achieve a 22% to 62% fuel-consumption improvement; engine HEVs, 52% to 75%; engine PHEV10s, 61% to 80%; and engine PHEV40s, 54% to 89%. Fuel-cell vehicles achieve an improvement of up to 79% for HEVs, 83% for PHEV10s, and 91% for PHEV40s.

Table ES-1: Percentage fuel-consumption reduction (mi/gal gasoline equivalent or MPGGE) of each powertrain by 2045, compared with reference 2013 gasoline conventional powertrain (Electrical consumption is not taken into account for PHEVs.)

Fuel\Powertrain	Conventional	HEV	PHEV10	PHEV40
Gasoline	28–50	57–74	67–79	81–89
Diesel	34–52	52–70	61–76	82–89
CNG	22–43	58–72	66–78	54-56
Ethanol	44–62	60–75	69–80	78-87
Fuel Cell		67–79	72–83	86-91

ES.2.2. EVOLUTION OF SPECIFIC POWERTRAINS

Table ES-2 shows the 2045 adjusted fuel-consumption reduction, on the combined driving cycle, for each powertrain configuration and fuel, compared with each configuration's current status in 2013 (e.g., the diesel HEV in 2045 is compared with the reference diesel HEV in 2013).

The results demonstrate that the maximum improvement expected for each powertrain technology compared with its current status ranges from 16% to 65%. The range depends on fuels (i.e., diesel vehicles show less improvement than gasoline vehicles) and powertrain (i.e., conventional engines have a lower maximum improvement than PHEV40s). When considering the entire uncertainty range, fuel-cell vehicles show the greatest improvement over time.

Table ES-2: Percentage fuel consumption reduction for each powertrain by 2045, compared with the respective current status (Values show uncertainty range.)

Fuel\Powertrain	Conventional	HEV	PHEV10	PHEV40
Gasoline	28–50	39–63	42–64	30–62
Diesel	21–43	33–58	33–59	34–59
Ethanol	16–40	46–64	46–65	46–65
CNG	43–62	38–60	38–59	27–59
Fuel Cell		31–58	31–59	32–58

ES.2.3. POWERTRAIN COMPARISONS

- Conventional Gasoline Vehicles versus Engine HEVs
  - The comparison between these powertrains shows that the fuel-consumption reductions due to hybridization increase over time for all power-split HEVs.
  - For gasoline HEVs, fuel-consumption reductions range from 38% to 46% for compact cars, 40% to 46% for midsize cars, 45% to 49% for small sport utility vehicles (SUVs), 43% to 47% for large SUVs, and 43% to 50% for pickup trucks.

- Conventional Gasoline Vehicles versus Engine PHEVs
  - As is the case for power-split HEVs, the fuel-consumption reduction observed for PHEVs relative to conventional gasoline vehicles remains fairly constant over time, ranging from 54% to 80% (PHEV10, 20, 30, and 40).
  - However, while the percentages decreased for higher vehicle weight classes, the benefits remained fairly constant across platforms.
- Conventional Gasoline Vehicles versus Fuel-Cell HEVs
  - The current fuel-consumption reductions for fuel-cell HEVs compared with conventional gasoline vehicles are 57% for midsize cars, 49% for small SUVs, 47% for large SUVs, and 45% for pickups.
  - Because of expected improvements in fuel-cell system and hydrogen-storage technologies, the fuel-consumption percentage improvements are expected to slightly increase over time. By 2045, the benefits will increase from 53% to 59%, depending upon the vehicle class and uncertainties considered. The reason why the increase is not larger is mainly due to the introduction of start/stop systems rather than a regular conventional vehicle in 2030.

- Engine HEVs versus Fuel-Cell HEVs
  - Fuel-cell system technology offers consistently lower fuel consumption than power-split HEV technology.
  - The current fuel-consumption benefits of fuel-cell HEVs compared with gasoline power-split HEVs are fairly constant across all vehicle classes and are around 31%.
  - Because of the engine and fuel-cell system operating conditions for HEVs, the fuel consumption improvement remains constant across all vehicle classes. However, the percentage is expected to decrease by 20% to 25% by 2045.

ES.2.4. EVOLUTION OF FUEL COMPARISONS

- Gasoline versus diesel
  - The differences between gasoline and diesel-engine fuel consumption for conventional vehicles will tend to decrease in the future.
  - For conventional vehicles, the fuel consumption advantage of diesel engines, when considering MPGGE, goes from 17% to 21% in 2013 to 5% to 9% by 2045.
  - For HEVs, the fuel consumption benefit of diesel is smaller than for conventional vehicles, ranging from 1% to 2% in 2013.
  - For PHEVs, the benefits of diesel compared with gasoline are minimal, ranging from 1% to 2% in 2013.
  - However, the diesel engine retains the best fuel consumption for the vast majority of uncertainties and timeframes.
- Ethanol
  - Ethanol-fuel conventional vehicles are expected to narrow their fuel consumption penalty over gasoline engines with time.
  - The fuel-consumption penalty for ethanol deceases for increased hybridization degree and battery energy.

ES.3. MANUFACTURING COST

Overall, the combination of technology improvements leads to significant manufacturing cost reduction across vehicle applications. As a result, advanced technologies are expected to have significant market penetration over the next decades.

ES.3.1. COST EVOLUTION COMPARED WITH REFERENCE 2013 GASOLINE CONVENTIONAL VEHICLE

Table ES-3 shows the additional manufacturing cost by 2045, compared with the reference gasoline conventional vehicle. The table shows a significant uncertainty range for the additional manufacturing cost across all technologies. This high uncertainty highlights the need to pursue aggressive research over the next decades to bring the cost of advanced technologies to a level that will favor high market penetrations.

Table ES-3: Additional manufacturing cost ($) of each powertrain by 2045, compared with reference 2013 gasoline conventional engine for midsize cars

Fuel\Powertrain	Conventional	HEV	PHEV10	PHEV40
Gasoline	3,100–3,600	4,300–4,900	4,500–5,400	5,200–7,000
Diesel	3,900–4,400	5,200–5,800	5,400–6,300	6,100–7,700
CNG	5,100–5,300	5,100–5,900	5,300–6,300	5,900–7,800
Ethanol	3,700–4,200	4,900–5,600	5,100–6,000	5,800–7,700
Fuel Cell		4,000–5,500	3,800–5,700	4,800–7,600
BEV-100	3,800–6,100			
BEV-300	7,800–12,000			

ES.3.2. EVOLUTION OF COSTS FOR SPECIFIC POWERTRAINS

Table ES-4 compares the percentage change in the manufacturing cost between 2013 and 2045 for each configuration relative to its current value.

Vehicle manufacturing costs for gasoline, diesel, compressed natural gas (CNG), and ethanol conventional vehicles increase over time because of several factors, including lightweighting and advanced component technologies such as direct injection. In contrast, the greatest reductions are noticed for the vehicles with high-energy batteries and fuel-cell systems.

Because of the expected improvements in batteries, the higher the battery energy, the greater will be the manufacturing cost reduction. As a result, PHEV40s demonstrate a larger cost reduction than PHEV10s across all fuels. PHEV40s with gasoline engines show cost reductions ranging from 9% to 44% from 2013 to 2045, while PHEV10s only show a cost reduction ranging from 2% to 25%.

The fuel-cell vehicle manufacturing costs decrease significantly over time. From 2013 to 2045, the manufacturing costs for the fuel-cell HEV decreases by 22% to 33%, for the fuel-cell PHEV10 by 22% to 34%, and for the fuel-cell PHEV40 by 30% to 43%.

Table ES-4: Percentage manufacturing cost reduction for each powertrain by 2045, compared with the respective current manufacturing cost, for midsize cars

Fuel\Powertrain	Conventional	HEV	PHEV10	PHEV40
Gasoline	(-) 10–27	1–14	3–15	13–26
Diesel	(-) 1–14	8–20	10–21	18–30
CNG	(-) 1–9	10–20	15–25	17–29
Ethanol	(-) 15–32	3–9	2–10	9–22
Fuel Cell		22–33	22–34	30–43
BEV-100	33–44			
BEV-300	50–65			

ES.3.3. POWERTRAIN COMPARISON

The manufacturing cost differences between different powertrain options tend to decrease over time. In 2013, for midsize cars, the gasoline power-split HEV is 37% more expensive than the conventional vehicle, the PHEV10 43% more expensive, and the PHEV40 78% more expensive. By 2045, these percentages are 6% for HEVs, 12% for PHEV10s, and 22% for PHEV40s.

ES.3.4. FUEL-COMPARISON EVOLUTION

- Gasoline versus diesel
  - The conventional diesel vehicle manufacturing cost will remain between 4% and 5% more expensive than gasoline vehicles by 2045.
  - The diesel HEV is between 13% and 14% more expensive to manufacture than the gasoline HEV vehicle, but this difference tends to decrease after 2013 and reach a range of 4% to 5% by 2045.

ES.4. CONCLUSION

The combination of the technology improvements leads to significant fuel consumption and cost reduction across light-duty vehicle applications. Because of the uncertainty of the evolution of the technologies considered, research should continue to be conducted in the different areas showing high fuel displacement potential.

Because of expected improvements, advanced technologies are expected to have a significant market penetration over the next decades. In the short term, both engine HEVs and PHEVs allow for significant fuel displacement with acceptable additional cost. While EVs do provide a promising solution, they are likely to remain expensive and range limited in the near future. For the long term, fuel cell vehicles demonstrate very high fuel displacement potential at a competitive cost

This research will be updated on a yearly basis to include the latest powertrain technologies and component technologies, as well as additional timeframes and vehicle applications.

1. INTRODUCTION

1.1. THE ENERGY SITUATION

The current international energy situation has brought about serious concerns in most of the developed countries about their use of fossil fuels and their need for developing renewable energy sources. This energy crisis takes place in the context of oil-stock reduction and a dramatic demand increase from developing countries. A study by Wang (2006) shows that Chinese on-road vehicles could consume up to 20.6 million bbl of oil per day by 2050. Moreover, China could face a tremendous increase in highway vehicles (including cars, trucks, and buses) in the next 40 years. Indeed, depending upon the case scenario developed in the study, there could be between 486 and 662 million highway vehicles in China in 2050, compared with roughly 27 million in 2004. Such a dramatic evolution could severely impact climate change and the oil market. The dilemma cannot be solved without creating new energy and/or transportation systems that either consume less oil or are not dependent on oil.

With a consumption of almost 19 million bbl/day, the United States is by far the world's highest-oil-consuming country. As illustrated in Figure 1, the United States, with only 4.5% of the world's population, consumes almost a quarter of the world's oil.

As shown in Figure 2, only 50% of the oil imported by the United States comes from the Western hemisphere; the rest is imported from other regions of the world. The unstable and unpredictable political situations in these other regions have led the United States to focus on reducing its oil dependency through various programs in different sectors.

The data shown in Figures 3 and 4 separate the total energy consumption by the transportation, industry, and other sectors according to energy type (e.g., coal, natural gas, oil, and nuclear). Although the development of nuclear, coal, and renewable energy could help decrease the need for oil in the industrial sector in the future, the primary focus should be the transportation sector, which is almost entirely dependent on oil as its primary energy source.

Such a strong dependence on oil has important consequences for the current world energy situation. As shown in Figure 5, in July 2008, the price of oil barrel exceeded $140/bbl, having doubled in less than a year. Consequently, the gasoline consumer price has also dramatically increased in past years, reaching the historic threshold of $4/gallon in the United States in June 2008. Even with a huge decrease at the end of 2008, the oil barrel price remains high in 2010 compared with what it was before the crisis.

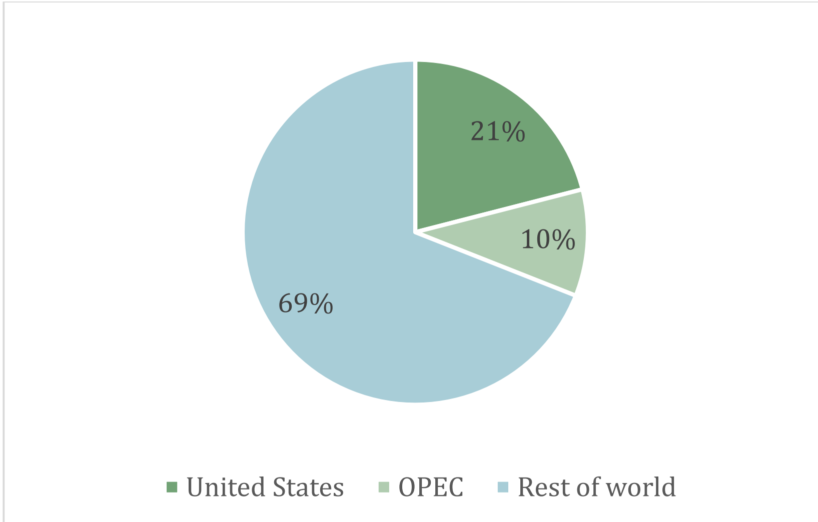


Figure 1 - Fraction of the world's oil consumption per country or continent data from [EIA1]

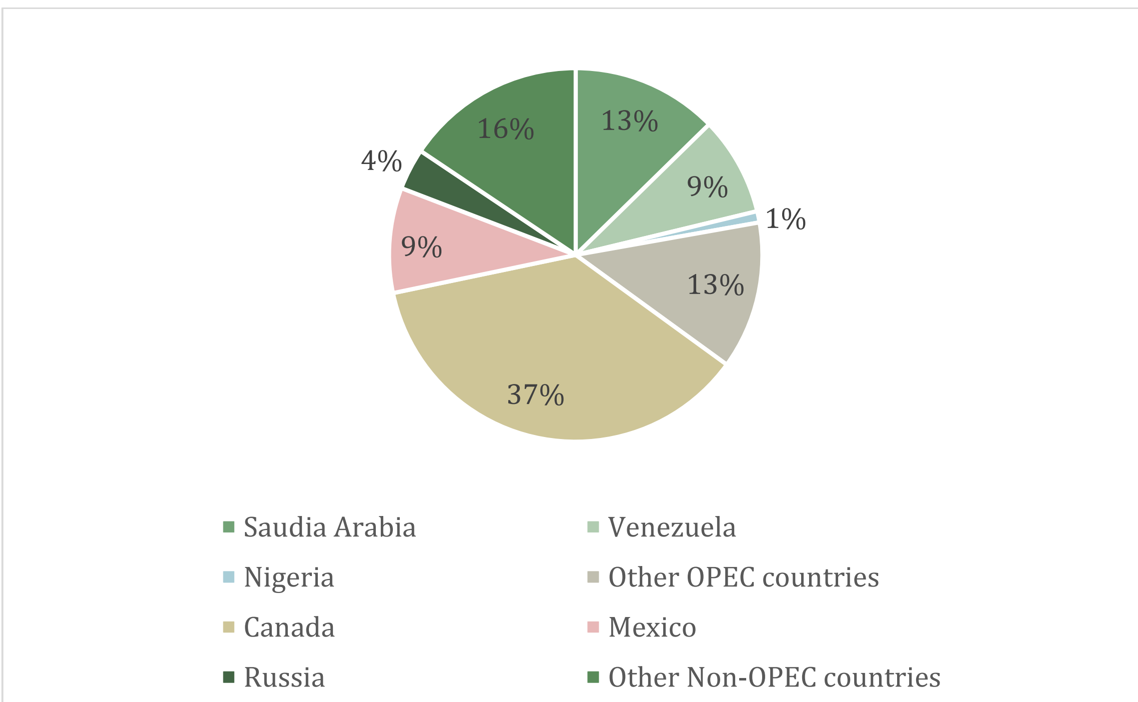


Figure 2 - Fraction of American imported oil per geographical region data from [EIA2]

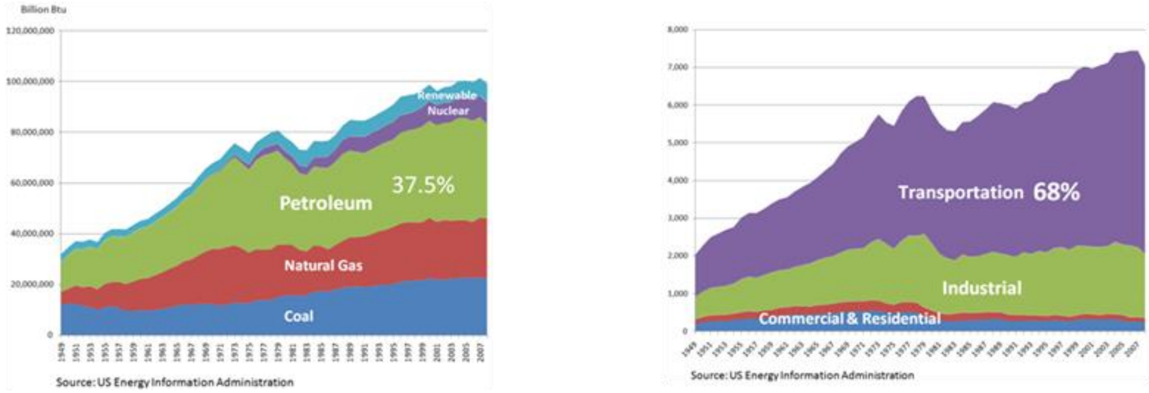


Figure 3 - U.S. consumption distribution (left) and role of transportation in global consumption (right)

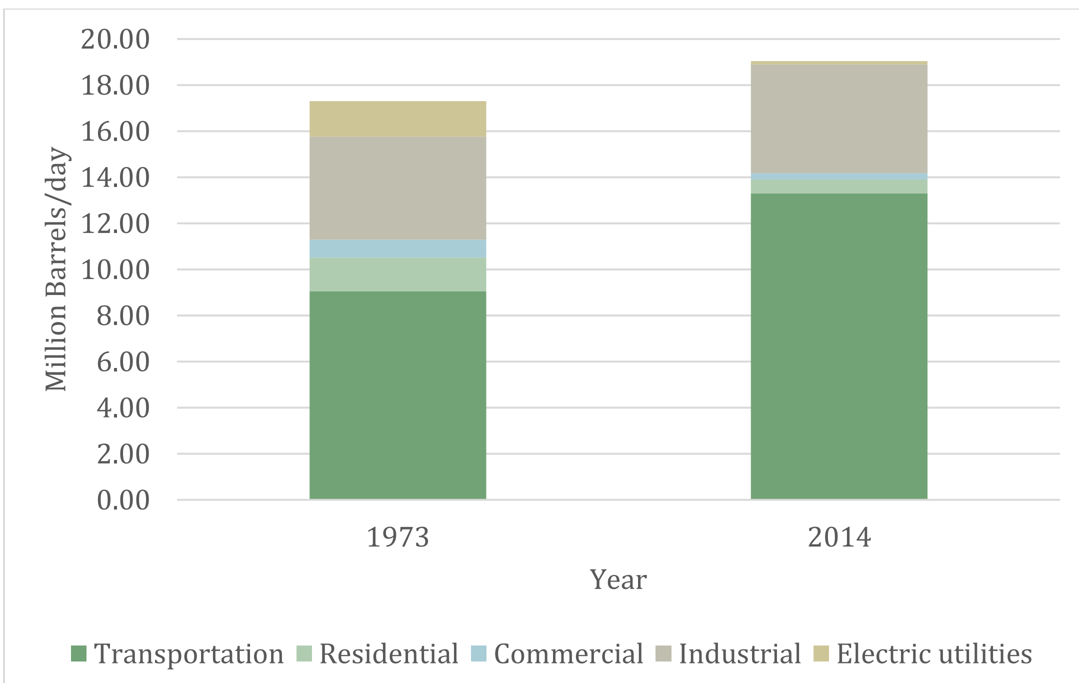


Figure 4 - Consumption of Petroleum by End-Use Sector, 1973–2014 data from [EIA3]

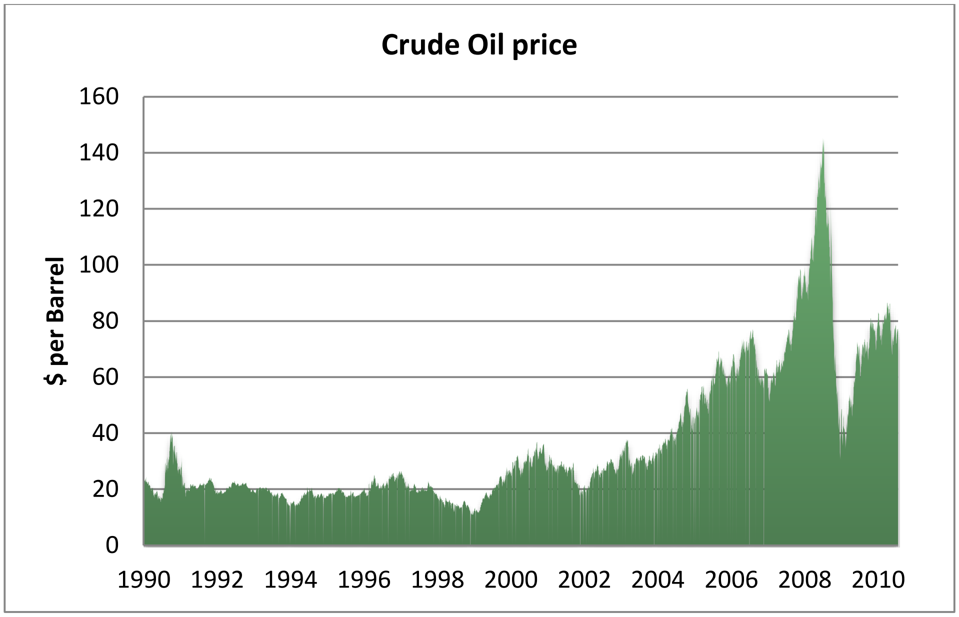


Figure 5 - Evolution of price of a barrel of oil from 1990 to 2010 data from [EIA4]

To address the issue, the U.S. government, and, in particular, the U.S. Department of Energy (DOE), has developed various projects to find alternative energy solutions for the transportation domain. Among the different possibilities that could be the key for the future, three main categories can be highlighted:

- The development of inexpensive and high-energy batteries to enable the commercialization of hybrid electric vehicles (HEVs) and plug-in hybrid electric vehicles (PHEVs). PHEVs would allow the driver to travel certain distances in electric-only mode and charge the vehicle overnight by plugging the car into the regular electric network.
- The development of biofuels such as ethanol. The current ethanol vehicles (also called flex-fuel or E85 vehicles) use a fuel made of 85% ethanol and 15% gasoline.
- The development of fuel-cell vehicles that would entirely eliminate oil dependency.

A DOE report (DOE 2010) states that the Obama Administration is investing in a broad portfolio of advanced vehicle technologies:

> *As part of the Department of Energy's $12 billion investment in advanced vehicle technologies, the Department is investing more than $5 billion to electrify America's transportation sector. These investments under the American Recovery and Reinvestment Act and DOE's Advanced Technology Vehicle Manufacturing (ATVM) Loan Program are supporting the development, manufacturing, and deployment of the batteries, components, vehicles, and chargers necessary to put millions of electric vehicles on America's roads.*

1.2. AMERICAN AUTOMOTIVE MARKET

The automotive market in the United States has greatly evolved over the past 30 years. These modifications include not only the distribution of vehicle types sold but also changes in performance, weight, and thus fuel consumption for all light-duty vehicles. Prior to the oil embargo of 1973, domestic oil was inexpensive and abundant, and car companies produced large and heavy cars with powerful engines and poor fuel economy. A combination of events, including increasing public desire for better fuel economy, increasing concern about carbon emissions that resulted in state regulations on fuel economy and carbon emissions, key court decisions, and a stated desire by the federal executive branch to decrease gasoline consumption, led to increasing Corporate Average Fuel Economy (CAFE) standards, which automakers preferred to state-level regulations.

Figure 6 shows the fuel-economy evolution for both cars and trucks. In 1975, a dramatic increase in the miles per gallon (mpg) began, and passenger-car fuel economy reached its peak in 1988, when cars averaged 24 mpg (a 71% improvement compared with 1975). However, since 1988, fuel economy has remained constant at around 23 mpg for cars, and if we consider all light-duty vehicles, it has even gradually declined from 1988 to 2004. Finally, since 2004, the light-duty vehicle adjusted fuel economy has increased from 20.2 mpg in 2006 to 21.2 mpg in 2009. Since tailpipe carbon dioxide (CO_2) emissions have an inverse relationship to fuel economy, emissions showed a rapid decrease from 1975 through 1981; a slower decrease to a valley in 1987; a gradual increase until 2004; and a decrease for the six years beginning in 2005, with the largest decrease in 2009. It is interesting to see that model year (MY) 2013 had the lowest CO_2 emission rate and highest fuel economy.

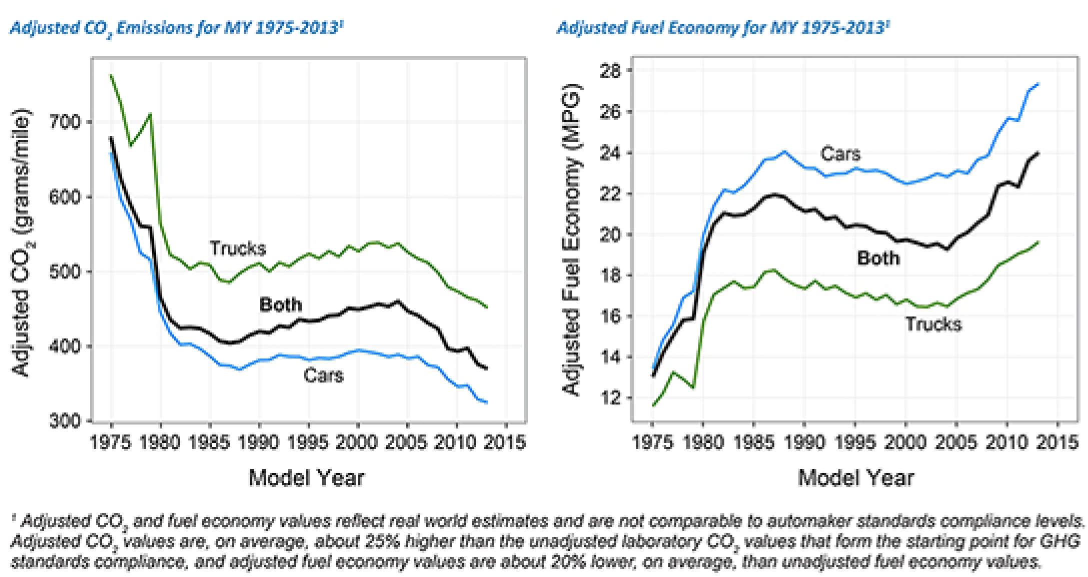


Figure 6 - Light-duty automotive technology, fuel economy, and emission trends: 1975 through 2013 (EPA 2013)

A study from the Civil Society Institute (CSI 2007) states that the average fuel economy of European light-duty vehicles is around 40 mpg, twice as high as in the United States. Also, CSI reports that, in 2008, only two cars in the United States (the Honda Civic Hybrid and the Toyota Prius) got 40+ mpg, whereas 113 cars in Europe could claim such an achievement. This means that more efficient vehicle technologies are available in the world, but because American customers prefer larger and more powerful cars, such as pickup trucks and sport utility vehicles (SUVs), the more efficient vehicles do not penetrate the U.S. automotive market.

Figure 7 shows the U.S. sales fractions for four different classes of light-duty vehicles: cars, SUVs, vans, and pickups. If we group the last three vehicle types under the truck category, we notice that nearly half of the light-duty vehicles sold in 2007 were "trucks." In addition, the truck sales fraction has been increasing for the past 20 years. However, because of higher gasoline prices in 2008, the pickup truck sales fraction decreased from 13% in February 2008 to 9.1% in May 2008 (DOE AutoInfoBank). Also, from June 2007 to June 2008, SUV sales dropped 54.7% and pickup truck sales dropped 35.6%, reflecting a deep change in consumers' behavior and expectations. Van and pickup truck sales continued to decrease in the following years until 2009. Truck market share is now at the lowest level since MY 1995. The MY 2010 light-truck market share is projected to be 41%, based on pre-MY production projections by automakers.

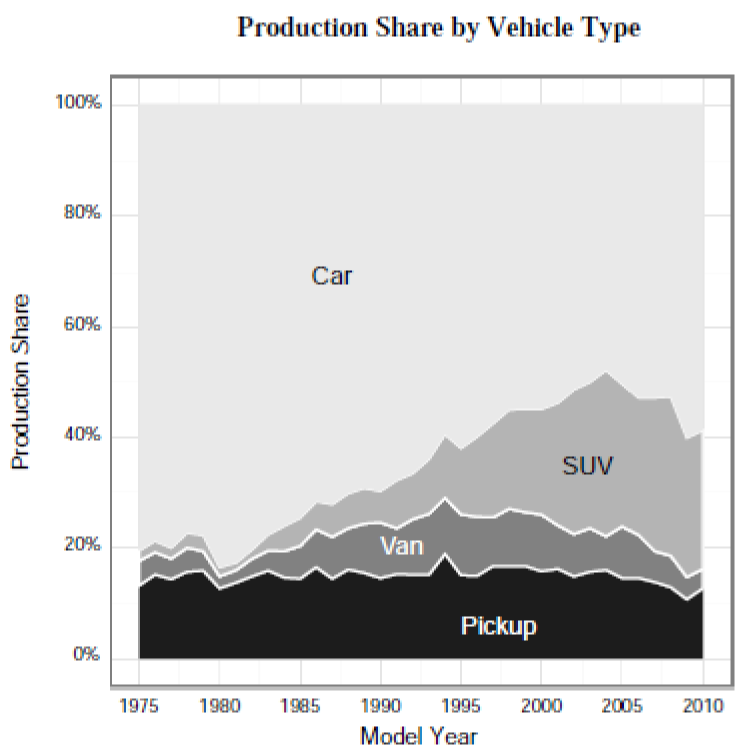


Figure 7 - Light-duty automotive technology and market share trends: 1975 through 2009 (EPA 2010)

In May 2008, for the first time in 17 years, the Ford F-150 pickup truck was not the best-selling light-duty vehicle in the United States. With 42,973 vehicles sold that month, it fell to fifth place after the Honda Accord (43,728), Toyota Camry (51,291), Toyota Corolla (52,826), and Honda Civic (53,299) (Autoblog 2008).

Vehicle weight and performance are two of the most important engineering parameters that help determine a vehicle's CO_2 emissions and fuel consumption. Figure 8 shows that MY 2009 light-vehicle weight averaged 3,917 lb, the lowest average weight since MY 2001. This weight reflects a decrease of 168 lb (4%) from MY 2008, and the largest annual decrease since MY 1980. The average truck weight dropped by about 100 lb, the average car weight dropped by about 60 lb, and the remaining difference was due to lower truck market share. In MY 2009, the average vehicle power was 208 horsepower, the lowest value since MY 2003. Average horsepower dropped by 11 (5%), the largest annual decrease since MY 1980, with most of the decrease explained by cars having lower horsepower levels and trucks having a lower market share. The four-cylinder-engine market share grew from 38% in MY 2008 to 51% in MY 2009 (and to nearly 70% for the car market). Estimated MY 2009 0-to-60 acceleration time remained constant at 9.7 seconds.

In summary, the American automotive market is steadily changing, with automakers trying to adapt their light-duty vehicle offerings to consumers' needs.

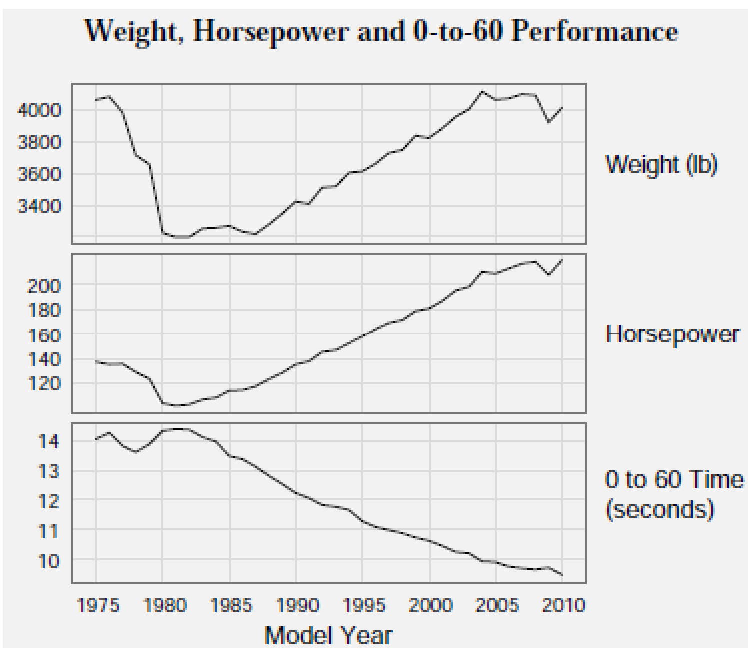


Figure 8 - Vehicle weight and performance evolution from 1975 to 2010

1.3. HYBRID ELECTRIC VEHICLES

1.3.1. CHARACTERISTICS

Hybrid electric vehicles (HEVs) are powered by at least two different sources of energy. In general, they combine an electrical storage system (i.e., battery, ultra-capacitor, etc.) and thermal source (i.e., engine, fuel-cell system, etc.).

The idea behind HEVs is to combine the advantages of conventional vehicles and battery-powered electric vehicles (BEVs), so as to limit the drawbacks of each. EVs have excellent efficiency, owing to high electric-machine efficiency (usually above 80% average on a cycle) and low battery losses. Furthermore, they can recover part of the energy usually lost during deceleration. For EVs, batteries are the critical component due to their cost and life.

An HEV offers the following features:

- **Idling stop**: The engine is turned off at zero vehicle speed to avoid idling. The engine is started using the electric machine. Depending on the electrical power available, the engine is started as soon as the vehicle moves (low power) or at higher vehicle speeds (high power).
- **Braking energy recovery**: The energy usually wasted by friction during deceleration can be recovered as electrical energy by an electric machine. The process is often called regenerative braking, as it regenerates (part of) the energy that the vehicle had to provide to overcome the effect of inertia when accelerating.
- **Low-speed electric machine propelling**: When the electric machine has sufficient power, it can be used alone to propel the vehicle, to avoid operating the engine at low load and low efficiency.
- **Electric machine assist**: At high power demand (i.e., when accelerating), the electric machine can assist the engine, allowing downsizing as well as lower transients and emissions.

The features mentioned above are not all available for all HEVs and depend on the powertrain configurations considered. Section 1.3.2 provides an overview of the main families of HEVs.

1.3.2. PRIMARY POWERTRAIN CONFIGURATIONS

The various HEV powertrain configurations can be classified on the basis of their hybridization degree, as shown in Figure 9. The hybridization degree is defined as the percentage of total power that can be delivered electrically. The higher the hybridization degree, the greater the ability to propel the vehicle using electrical energy.

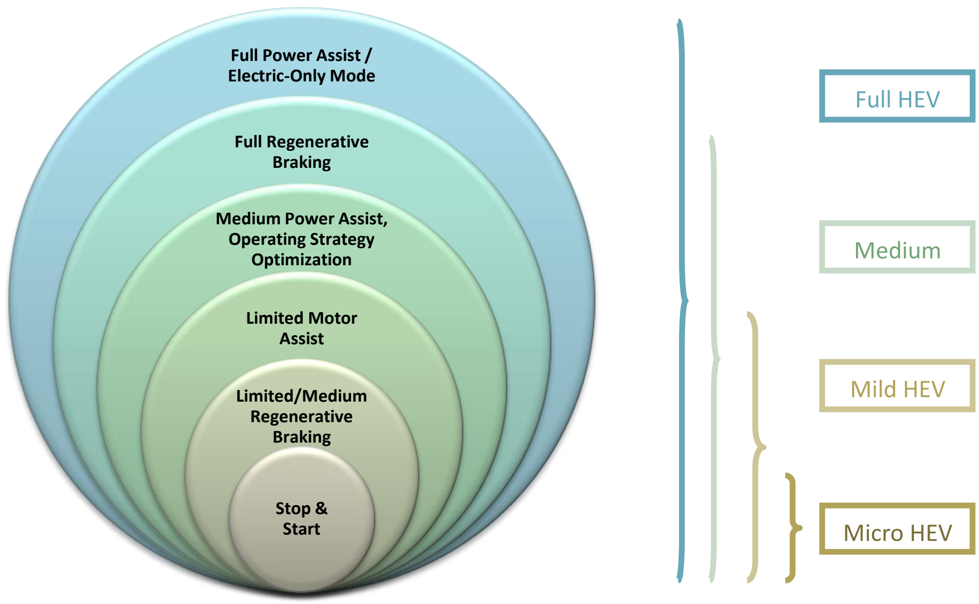


Figure 9 - Hybridization degree

There are numerous hybrid powertrain designs. The main families are described below and illustrated in Figure 10.

Series Configuration

The first hybrids were generally based on a series configuration. In this case, the vehicle is propelled solely by electrical energy. When an engine is used, it provides a generator with mechanical power, which then converts it into electricity. In the case of a fuel-cell system, the electrical energy is directly used by the electric machine. The main advantage is that the engine speed is decoupled from the vehicle speed, allowing an operating condition at or close to its most efficient operating point. The main drawback is that the main components have to be oversized to be able to maintain the same performance, which leads to higher vehicle weight. Finally, the large number of components leads to a low powertrain efficiency.

Parallel Configuration

In a parallel configuration, the vehicle can be directly propelled by either electrical or mechanical power. Direct connection between the energy sources and the wheels leads to lower powertrain losses compared with the pure series configuration. However, since all of the components' speeds are linked to the vehicle's speed, the engine cannot constantly be operated close to its best efficiency curve.

Several subcategories exist within the parallel configuration:

- Start-stop: A small electric machine is used to turn the engine OFF when the vehicle is stopped. Examples include the Citroen C3.
- Starter-alternator: This configuration is based on a small electric machine (usually 5 to 15 kW) located between the engine and the transmission. Because of the low electric-machine power, this configuration is mostly focused on reducing consumption by eliminating idling. While some energy can be recuperated through regenerative braking, most of the negative electric-machine torque available is usually used to absorb the engine's negative torque. Examples include the Honda Civic, Honda Accord, and Citroen C3.
- Pre- and post-transmission: Both configurations allow the driver to propel the vehicle in electric-only mode as well as recover energy through regenerative braking. The electric-machine power usually ranges from 20 to 50 kW. The main difference between these two options is the location of the electric machine (before or after the transmission). The post-transmission configuration has the advantage of maximizing the regenerative energy path by avoiding transmission losses. On the other hand, the pre-transmission configuration can take advantage of different gear ratios that allow the electric machine to operate at higher efficiency and provide high torque for a longer operating range.

Power-Split Configuration

The power-split configuration, composed of an engine and two electric machines, allows both parallel and series paths. The main feature is that all component speeds are decoupled, which allows a higher degree of control.

Each configuration is represented in Figure 10.

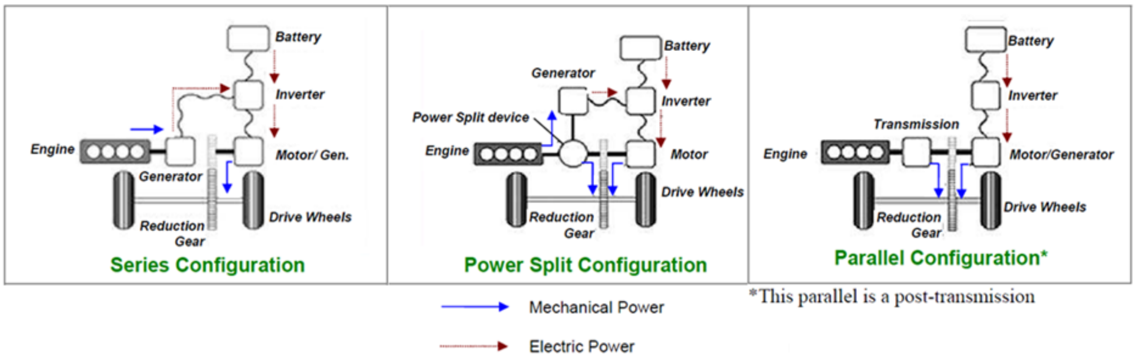


Figure 10 - Hybrid powertrain configurations

It is important to note that many different variations exist within each configuration (e.g.., power-split configurations can be single-mode, two-mode, or three-mode) and among configurations (i.e., several configurations are considered to be a mix of series, parallel and/or power-split). Overall, several hundred configurations are feasible for electric-drive vehicles (EDVs).

1.3.3. HEV MARKET

Figure 11 shows the evolution of the hybrid-vehicle market from 1999 to November 2014. The first HEV introduced in the American market was the Honda Insight in 1999. It is a small two-seater with an aggressive design that has had limited success despite its excellent fuel economy (49 mpg city and 61 mpg highway in MY 2000, according to the U.S. Environmental Protection Agency [EPA]).

Toyota released its first Prius in the United States in 2000, and Honda released its hybrid version of the popular Civic in 2002. After a redesigned, larger version of the Prius was released in 2004, Prius sales significantly increased and exceeded sales of the hybrid Civic.

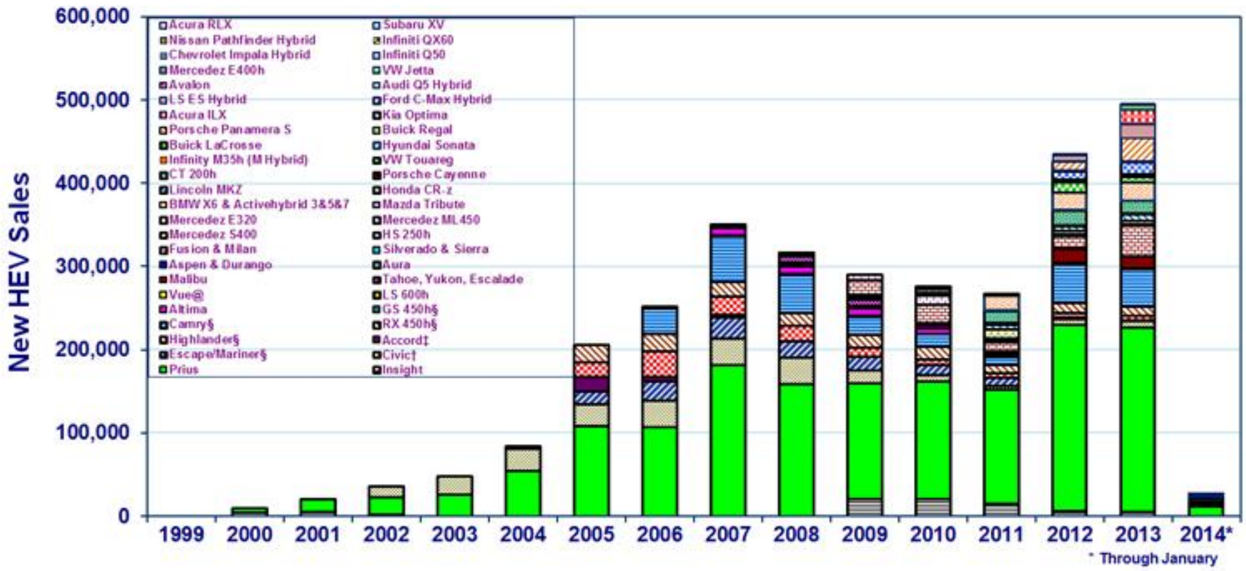


Figure 11 - HEV sales in the United States from 1999 to November 2014 (Source: Zhou and Vyas, 2013)

Since 2000, the hybrid vehicles offered have expanded across multiple carmakers and vehicle classes. Some SUVs (e.g., Toyota Highlander, Ford Escape, and Tahoe HEV) are now hybrid vehicles. In 2007, hybrid-vehicle sales increased by 38% compared with 2006 and represented 2.2% of the total vehicle sales in the United States. Several reasons explain the decrease of hybrid-vehicle sales since 2007:

1. Total vehicle sales decreased during that period,
2. Economic conditions made people cautious about investing in a more expensive technology, and
3. The price of fuel dropped.

The results can be seen clearly in Figure 12.

As shown in Figure 13, hybrid vehicle sales also correlate with gasoline prices, since people are more likely to invest in an EDV if gasoline prices are high. For example, between April 2008 and October 2008, the U.S. average gasoline price decreased from $4.10 per gallon to $1.80 per gallon. Simultaneously, hybrid-vehicle sales decreased by more than 50%, with only 15,000 vehicles sold in January 2009. Figure 14 shows sales from 2010 to 2014 for PEVS by model.

Figure 15 shows worldwide sales of various types of hybrid vehicles as percentages of total sales from 1999 to 2014. In 2013, 6% of cars (midsize and large) were HEVs, whereas roughly 0.5% of light trucks (SUVs, trucks, vans) were HEVs.

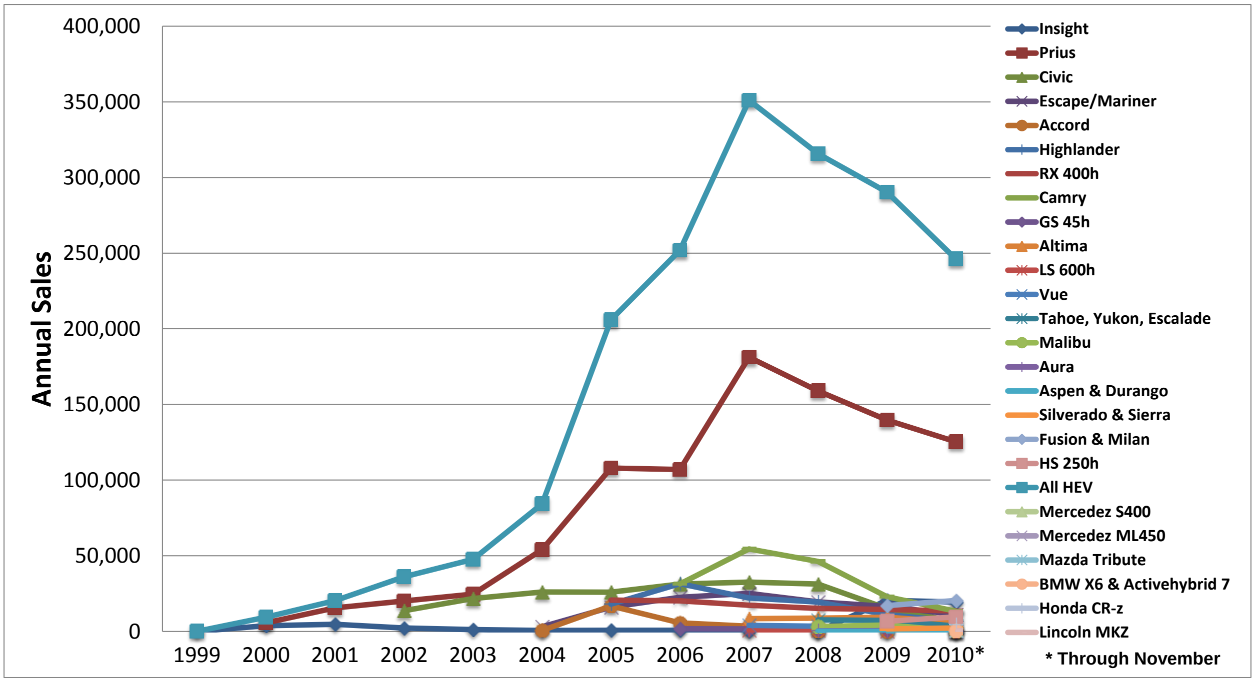


Figure 12 - U.S. HEV sales trends from 1999 to November 2010 (Source: Zhou and Vyas, 2013)

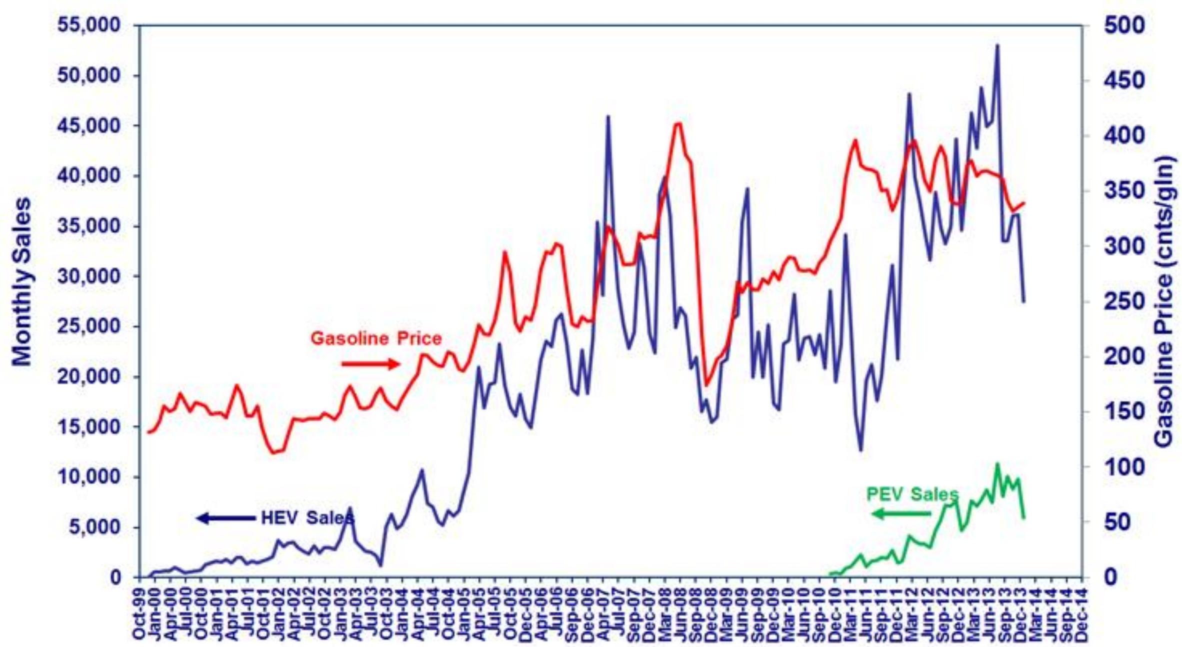


Figure 13 - Monthly new EDV sales and gasoline price

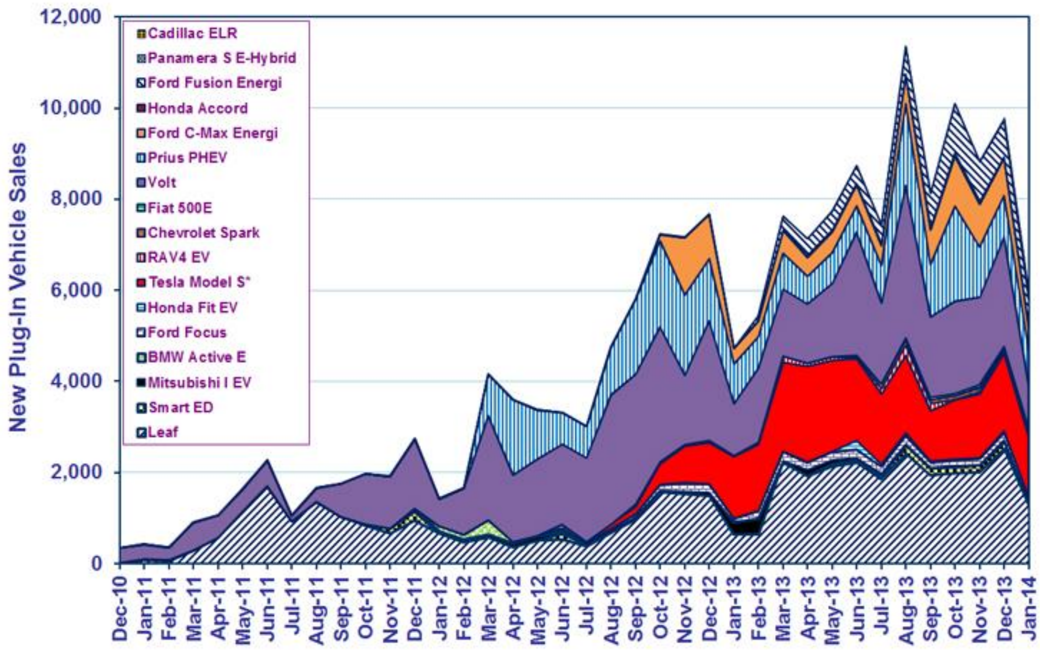


Figure 14 - U.S. gasoline prices and HEV sales, 2010–2014 (Source: Zhou and Vyas, 2013)

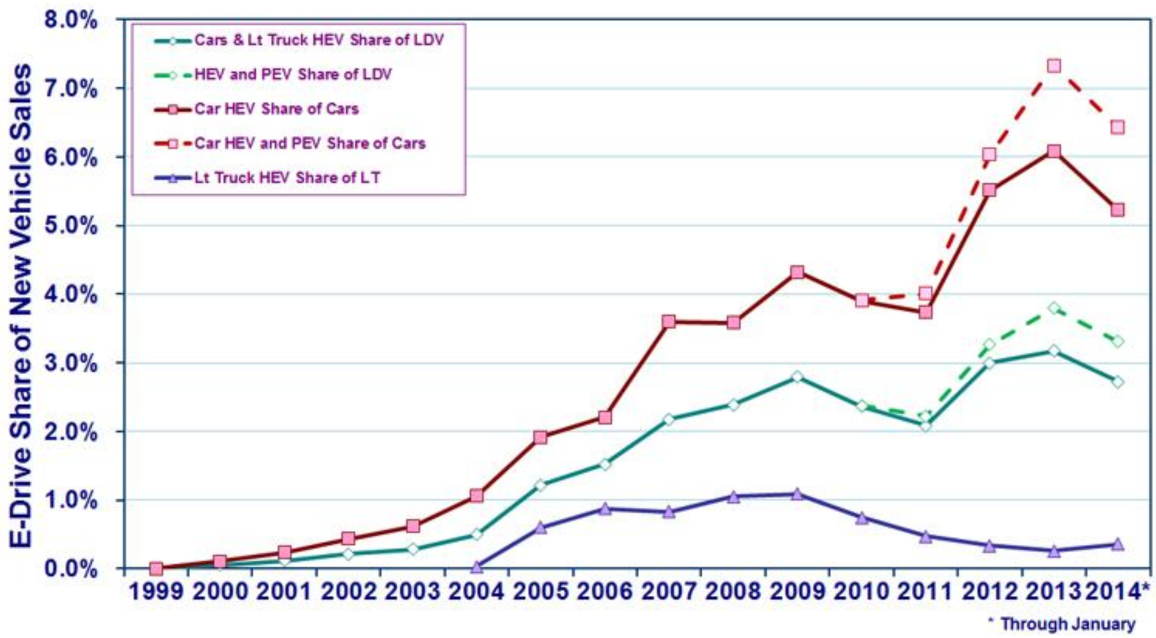


Figure 15 - HEV car and light-truck sales as share of worldwide vehicle sales (Source: Zhou and Vyas, 2013)

1.4. PLUG-IN HYBRID ELECTRIC VEHICLES

1.4.1. DEFINITION AND CHARACTERISTICS

A PHEV, also called grid-connected HEV or extended-range EV (E-REV), is an HEV whose batteries can be charged from a wall-outlet. In other words, the energy storage system can be plugged into an external electric-power source. Because of their ability to be recharged from an outlet, PHEV batteries have a lower power-to-energy ratio compared with their HEV counterparts. In addition, the increase in energy capacity for PHEV batteries versus HEV batteries is more substantial than the increase in power requirements for PHEV batteries versus HEV batteries. Their higher energy and power allow extended usage of the electric-only mode, leading to fewer engine ON/OFF cycles. While the engine is started at a power demand of ~7-9 kW at the wheel for most HEVs, a PHEV offers the ability to start it later, at from 10 to 30 kW, depending on the battery's available energy, its state of charge (SOC), and the trip distance.

Because of their ability to operate mostly in all-electric mode, PHEVs offer a very promising solution to fuel displacement. PHEVs share the same powertrain components as HEVs, with a higher hybridization degree. However, the vehicle's ability to operate in electric mode requires different energy storage system technology compared with current hybrids:

- **Higher energy**: the batteries have higher capacity and discharge range, as a function of all-electric range (AER);
- **Higher power**: the electric system is in general more powerful, to be able to be the only source of power in a wider range of situations; and
- **Increased control freedom**: the higher degree of hybridization allows a greater number of possible electric-machine/engine-power combinations, leading to significant added complexity in determining the optimal control strategy compared with HEVs.

The DOE envisions a key future role for HEVs and PHEVs in reducing oil consumption and enabling a dramatic shift from petroleum-based transportation fuels to electricity, taking advantage of U.S. investments in renewable energy that will result in a flexible, clean, and reliable power generation and distribution system in the future. In January 2013, DOE released its *Grand Challenge Blueprint: EV Everywhere*. The plan is based on early benchmark testing of PHEV conversion vehicles (i.e., stock hybrids with added battery capacity and control modifications), vehicle modeling and simulation, and the status of batteries, power electronics, and electric motors in the DOE technology research and development (R&D) programs.

1.4.2. CHALLENGES

Battery Technology

Batteries are the most critical technology for PHEVs. They are characterized by

- High capacity, for greater AER (charge depleting [CD]);
- High power, to meet the power demand in all-electric mode;
- High range of SOC use; while conventional hybrids use between 10% and 15% of the total battery energy, PHEVs use a larger percentage (e.g., 65% for the GM Volt or higher for other prototypes);
- Longer continuous periods of discharge and recharging; and
- Thermal management issues (heating).

The last two points have a major impact on battery life and performance variation.

Lithium batteries are believed to be the best solution at the present time, as they possess twice the specific energy of nickel metal hydride (NiMH) batteries. However, they require sophisticated battery-management systems and significant circuitry to prevent overcharging and overdischarge. Some safety problems remain to be solved. Further battery R&D is still needed before long-life, compact, and inexpensive batteries are available. The future market penetration of PHEVs will depend greatly on the success of battery R&D. Figure 16 shows the current status of lithium-ion (Li-ion) batteries compared with DOE goals.

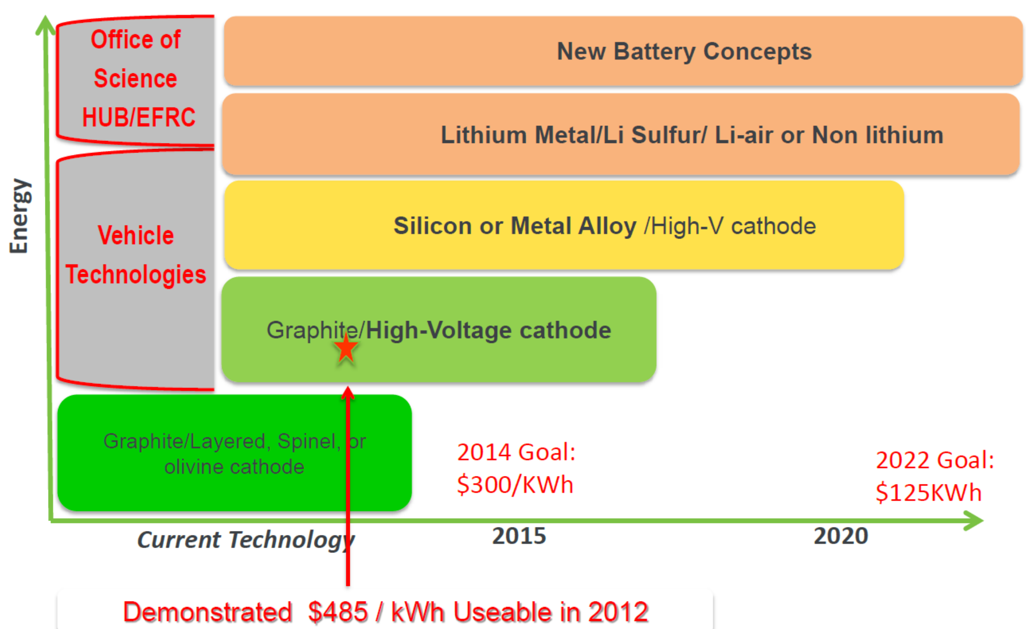


Figure 16 - Status of Li-Ion batteries versus DOE goals (Source: Howell 2013)

Electric Machine and Power Electronics

The electric-drive system entails substantial technical and economic challenges as well. PHEVs with full performance (i.e., competitive acceleration and top speed) in electric mode require power electronics and electric motors with twice the power of today's hybrids—at lower cost (this requirement is, however, not considered a "showstopper"). And the need for "smart" onboard battery chargers (to ensure efficient and cost-effective recharging) adds more pressure for cost reduction.

Vehicle System

Special attention has to be paid to the design of the vehicle as a system. Because of the existence of two power sources, multiple design and control choices affect overall efficiency. For PHEVs, one of the key questions is the degree of hybridization, and more particularly, the "zero emission mode." Will the electric machine provide all the mechanical power or will it be assisted by the intermittent use of the engine? If so, what will be the level of this assistance? Each possible solution has to be considered and the environmental/economic benefits assessed. Several studies have been published to assess the impact of powertrain configuration and component sizing on fuel efficiency (Sharer et al. 2007; Fellah et al. 2009), but more work needs to be performed.

Advanced energy management control strategies will provide the opportunity to use the vehicle at its optimum efficiency (Karbowski et al. 2006; Rousseau and Moawad 2010; Moawad and Rousseau 2012); however, additional applied R&D will be required. One of the current research approaches is to adapt the control strategy to the trip conditions and even to the driver's behavior through global optimization.

The ultimate goal is to develop a vehicle that would be beneficial from a macroscopic as well as a customer point of view. Driving habits and patterns have to be reviewed to design one or several types of PHEVs that would be potentially adapted to a significant number of customers.

Charging Infrastructure

Charging at home will require appropriate circuits: 220-V AC is preferred for Level 2 charging of vehicles with longer electric ranges, compared with the standard U.S. household receptacle voltage of 110 V. Innovative solutions will have to be found to provide convenient charging locations (e.g., in garages, parking lots, and other structures) for those who do not have private garages.

In order to prepare for a significant market penetration of PHEVs, utilities have to develop their generation facilities as well as specific management of their generation, transmission, and distribution assets to balance the impact of PHEVs on the grid. Specific generation sites can also be developed, such as wind turbines for night charging, or "solar" parking for day-charging. The possibility of bidirectional energy flow between the grid and PHEVs will require communication systems to optimize the leveling effect. Numerous studies have been performed and are currently under way to examine these issues (Morrow et al. 2008).

1.5. INPUT DEVELOPMENTS

The inputs for the present study (i.e., component assumptions, control strategies, VTS, sizing algorithms, etc.) were developed over several years through numerous discussions with both components and systems experts.

To define an assumption, several experts were contacted independently to provide their input related to their area of expertise for each uncertainty and timeframe considered. At least three experts were contacted before defining an input. The assumptions will be discussed in detail in Chapter 3.

2. METHODOLOGY

2.1. AUTONOMIE OVERVIEW

Many of today's automotive control-system simulation tools are suitable for simulation, but they provide rather limited support for model building and management. Setting up a simulation model requires more than writing down state equations and running them on a computer. With the introduction of EDVs, the number of components that can populate a vehicle has increased considerably, and more components translate into more possible drivetrain configurations. In addition, building hardware is expensive. Traditional design paradigms in the automotive industry often delay control-system design until late in the process—in some cases requiring several costly hardware iterations. To reduce costs and improve time to market, it is imperative that greater emphasis be placed on modeling and simulation. This only becomes truer as time goes on because of the increasing complexity of vehicles and the greater number of vehicle configurations.

With the large number of possible advanced vehicle architectures and time and cost constraints, it is impossible to manually build every powertrain configuration model. As a result, processes have to be automated.

Autonomie (Argonne 2011a; Rousseau n.d.) is a MATLAB©-based software environment and framework for automotive control-system design, simulation, and analysis. The tool is designed for rapid and easy integration of models with varying levels of detail (low to high fidelity) and abstraction (from subsystems to systems and entire architectures), as well as processes (e.g., calibration, validation). Developed by Argonne National Laboratory (Argonne) in collaboration with General Motors, Autonomie was designed to serve as a single tool that can be used to meet the requirements of automotive engineering throughout the development process from modeling to control. Autonomie was built to accomplish the following:

- Support proper methods, from model-in-the-loop, software-in-the-loop, and hardware-in-the-loop to rapid-control-prototyping;
- Integrate math-based engineering activities through all stages of development, from feasibility studies to production release;
- Promote re-use and exchange of models industry-wide through its modeling architecture and framework;
- Support users' customization of the entire software package, including system architecture, processes, and post-processing;
- Mix and match models of different levels of abstraction for execution efficiency with higher-fidelity models where analysis and high-detail understanding are critical;
- Link with commercial off-the-shelf software applications, including GT-Power©, AMESim©, and CarSim©, for detailed, physically based models;

- Provide configuration and database management; and
- Protect proprietary models and processes.

By building models automatically, Autonomie allows the simulation of a very large number of component technologies and powertrain configurations. Autonomie can do the following:

- Simulate subsystems, systems, or entire vehicles;
- Predict and analyze fuel efficiency and performance;
- Perform analyses and tests for virtual calibration, verification, and validation of hardware models and algorithms;
- Support system hardware and software requirements;
- Link to optimization algorithms; and
- Supply libraries of models for propulsion architectures of conventional powertrains as well as EDVs.

Autonomie will be used to assess the fuel consumption and cost of advanced powertrain technologies. Autonomie has been validated for several powertrain configurations and vehicle classes using Argonne's Advanced Powertrain Research Facility (APRF) vehicle test data (Kim et al. 2009; Rousseau et al. 2006; Cao 2007; Rousseau 2000; Pasquier et al. 2001).

With more than 400 different pre-defined powertrain configurations, Autonomie is an ideal tool for analyzing the advantages and drawbacks of the different options within each family, including conventional, parallel, series, and power-split hybrid vehicles. Various approaches have been used in previous studies to compare options ranging from global optimization (Karbowski et al. 2009) to rule-based control (Freyermuth et al. 2008).

Autonomie also allows users to evaluate the impact of component sizing on fuel consumption for different powertrain technologies (Nelson et al. 2007; Karbowski et al. 2007) as well as to define the component requirements (e.g., power, energy) to maximize fuel displacement for a specific application (Fellah et al. 2009; Rousseau et al. 2004). To properly evaluate any powertrain-configuration or component-sizing impact, the vehicle-level control is critical, especially for EDVs. Argonne has extensive expertise in developing vehicle-level controls based on different approaches, from global optimization to instantaneous optimization (Karbowski et al. 2010), rule-based optimization (Sharer et al. 2008), and heuristic optimization (Rousseau et al. 2008).

The ability to simulate a large number of powertrain configurations, component technologies, and vehicle-level controls over numerous drive cycles has been used to support many DOE as well as manufacturers' studies. These studies focused on fuel efficiency (Delorme et al. 2008), cost-benefit analysis (Rousseau et al. 2005), or greenhouse gases (GHGs) (Elgowainy et al. 2009; Wu et al. 2006). All the development performed in simulation can then be implemented in hardware to take into account non-modeled parameters such as emissions and temperature (Vijayagopal et al. 2010).

Autonomie is the primary vehicle simulation tool selected by DOE to support its FreedomCAR Program and Vehicle Technologies Program (VTP) (DOE n.d.[b]; Vehicle Systems Analysis Technical Team [2006]). Autonomie has been used for numerous studies to provide the U.S. government with guidance for future research (www.autonomie.net). More than 150 companies and research entities, including major automotive companies and suppliers, are also using Autonomie to support advanced vehicle development programs.

2.2. STUDY PROCESS

The process to estimate the fuel consumption of various advanced powertrains can be divided into three steps:

- **Define the Architecture**
  The vehicle architecture is built using the different components available in the main database. In this study, each component is associated with different uncertainties (low, average, and high) (see Section 2.3).

- **Size the Components**
  Algorithms are used to size the vehicle components to compare vehicles with the same Vehicle Technical Specifications (VTS). Once the sizing is complete, all the components' features are known, and thus it is possible to estimate the retail price of the vehicle. The sizing algorithms are specific for each configuration and will be discussed later in detail.

- **Run the Simulation**
  The third step calculates the vehicle fuel consumption by simulating the different standard U.S. test procedures.

2.3. TIMEFRAMES AND UNCERTAINTIES

To evaluate the fuel-efficiency benefits of advanced vehicles, each vehicle is designed from the ground up based on each component's assumptions. The fuel efficiency is then simulated using the Urban Dynamometer Driving Schedule (UDDS) and Highway Federal Emissions Test (HWFET) cycles. The vehicle costs are calculated from the component characteristics (e.g., power, energy, weight). Both cost and fuel efficiency are then used to define the market penetration of each technology to finally estimate the amount of fuel saved. The process is highlighted in Figure 17. This report will focus on the first phase of the project: fuel efficiency and cost.

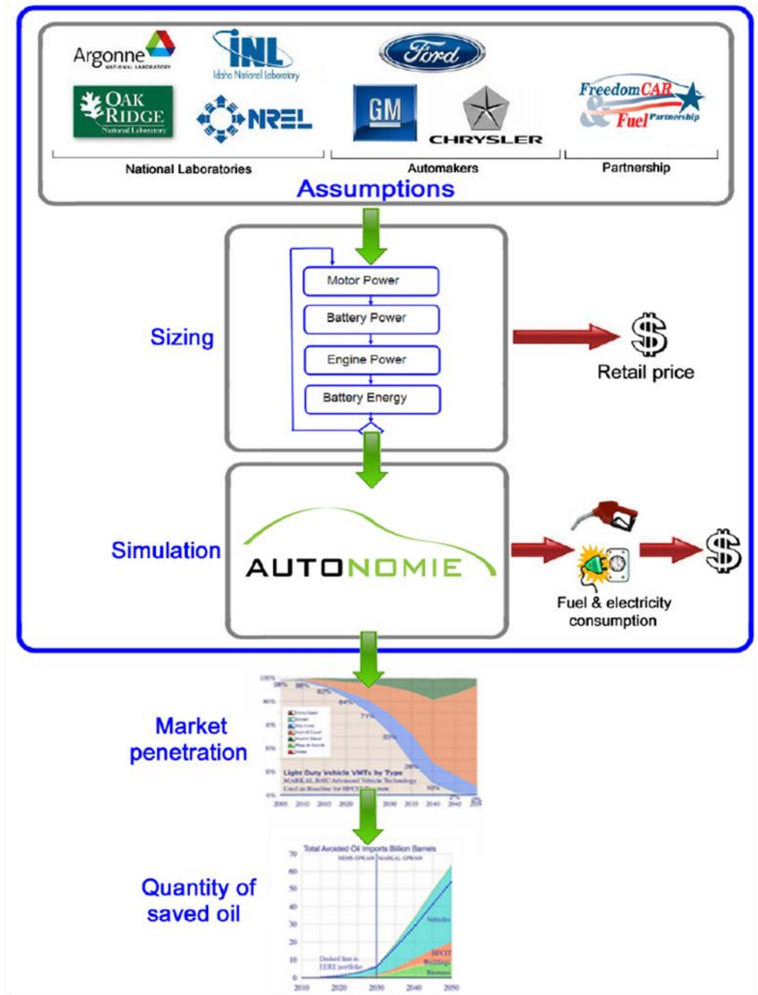


Figure 17 - Process to evaluate fuel efficiency of advanced vehicle technologies

To properly assess the benefits of future technologies, several options were considered, as shown in Figure 18:

- Five vehicle classes: compact, midsize car, small SUV, medium SUV, and pickup truck
- Five timeframes: reference 2013, 2015, 2020, 2030, and 2045
- Five powertrain configurations: conventional, HEV, PHEV, fuel-cell HEV, and EV
- Four fuels: gasoline, diesel, ethanol, and CNG
- Three risk levels: low, average, and high. These correspond, respectively, to 10% uncertainty (aligned with original equipment-manufacturer [OEM] improvements based on regulations), 50% uncertainty, and 90% uncertainty (aligned with aggressive technology advancement based on the DOE VTP). These levels are explained more fully below.

Overall, more than 2,000 vehicles were defined and simulated in Autonomie. The study does not include mild hybrids and does not focus on emissions. Micro hybrid technology is introduced starting in 2030 to replace conventional vehicles.

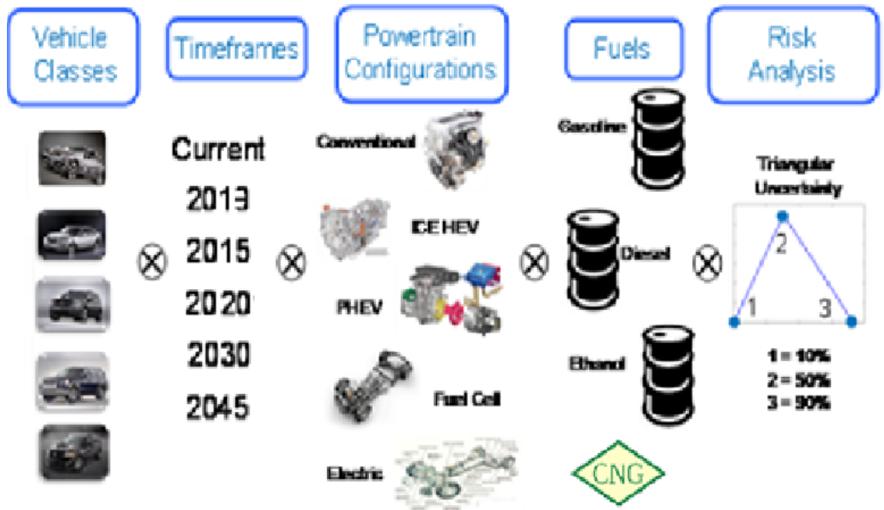


Figure 18 - Vehicle classes, timeframes, configurations, fuels, and risk levels considered

When dealing with uncertainties, numerous methodologies are available. In previous studies, Argonne has compared Monte Carlo simulation with a triangular distribution analysis (Faron et al. 2009). By allowing the introduction of uncertainty into our algorithm inputs, the Monte Carlo method increases the amount of useful information to describe a vehicle's possible behaviors. The major improvement concerns the introduction of the risk notion associated with each result. Rather than providing a single forecast value, Monte Carlo simulation provides the probability of occurrences associated with every possible output value. As a result, forecasts are more fully and accurately described, and confidence intervals can be derived for each output.

The results from Monte Carlo simulations based on a midsize PHEV were defined, providing a mode for both fuel economy and cost within a certain confidence interval. The approach was then compared with the existing three-point option. Results demonstrated that, as expected, Monte Carlo simulation provided a narrower range. However, increasing the amount of information available in the results has a computational cost. The experiments carried out so far led us to a first evaluation of the number of points required to simulate. This number varies from 100 to 200, depending on the number of uncertain inputs considered. While computational time varies for each configuration, the average time required to simulate a PHEV on all these points was 150 minutes.

Because of the large number of vehicles considered in the study, the triangular distribution approach (low, average, and high) was employed, as shown in Figure 19. For each component, assumptions were made (i.e., efficiency, power density), and three separate values were defined to represent the (1) 90th percentile, (2) 50th percentile, and (3) 10th percentile. A 90% probability means that the technology has a 90% chance of being available at the time considered. For each vehicle considered, the cost assumptions also follow the triangular uncertainty. Each set of assumptions was, however, used for each vehicle, and the most efficient components were not automatically the cheapest ones. As a result, for each vehicle considered, we simulated three options for fuel efficiency. Each of these three options also had three values representing the cost uncertainties. A more detailed description of the uncertainty process is available (Henrion 2008).

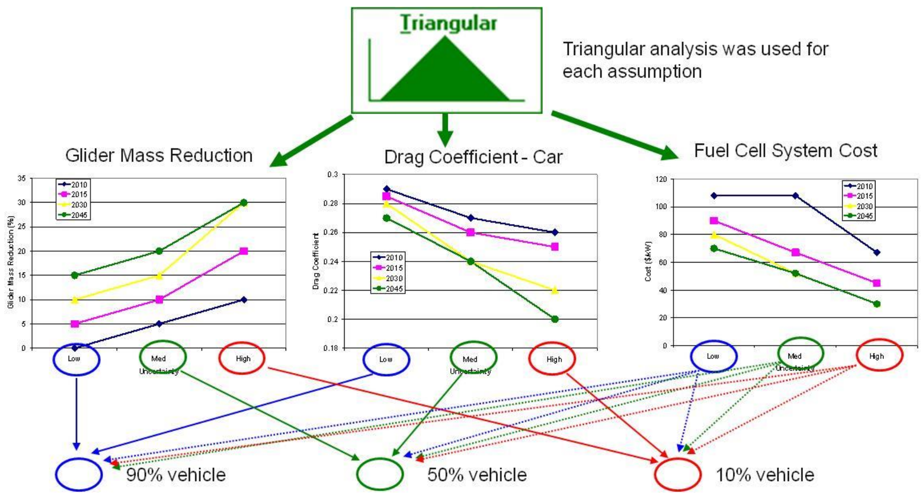


Figure 19 - Uncertainty process description

The “reference case” used in the study was considered to be the low-uncertainty 2013 case.

2.4. COMPUTER CLUSTER UTILIZATION

As shown previously, the number of combinations is very large, since a very large number of vehicles need to be sized and simulated. Taking into account that the sizing algorithms run as an iterative process, it becomes clear that a lot of simulating and calculating power is required from the computer hardware system. For such applications, a high-performance computing center is available at Argonne. It is composed of a stack of 128 calculating machines and a server computer.

An algorithm was developed for optimizing the distribution of jobs for vehicle simulations and parametric studies (Mathworks n.d.; Pagerit 2007). This system (Figure 20) was used to run the entire study. However, even with this powerful tool, the total simulation time was about 15 hours for sizing and 10 hours for simulation. This distributive computing operation tremendously decreased the sizing and simulation time, which otherwise would have taken many weeks. The distributed computing also greatly facilitated the reruns of simulations, which occurred numerous times during this study.

Figure 20 - Matlab distributive computing process diagram

3. COMPONENT ASSUMPTIONS

The assumptions for each component were developed in collaboration with experts from DOE, national laboratories, industry, and academia. The following paragraph represents a compromise reached by the authors of the study and should not be attributed to any specific company.

Several hundred assumptions are required to run a single vehicle simulation. Figures 21 and 22 show a short list of these assumptions for the components and vehicles, respectively. The following sections only provide information regarding a very limited set of assumptions, since most of the assumptions were provided by industry partners and are considered proprietary.

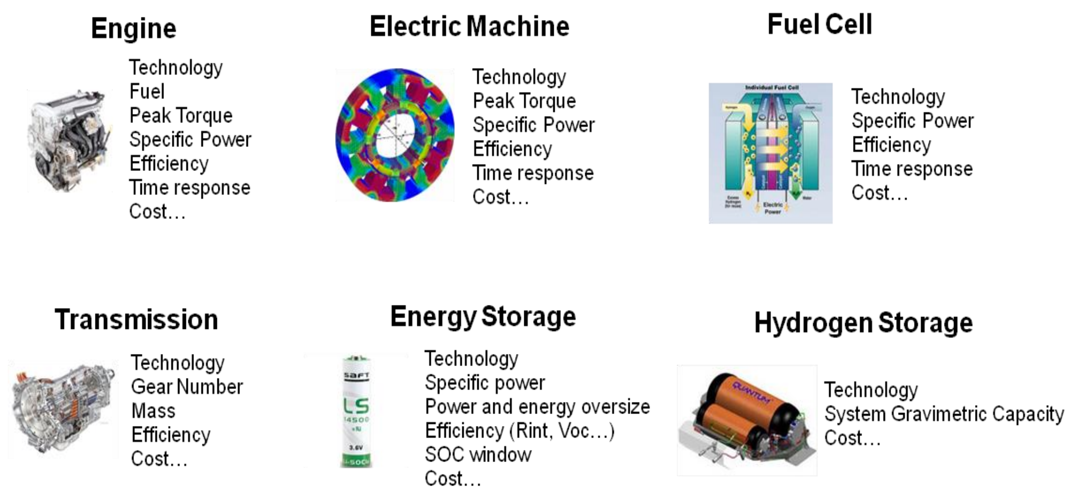


Figure 21 - Main component assumptions

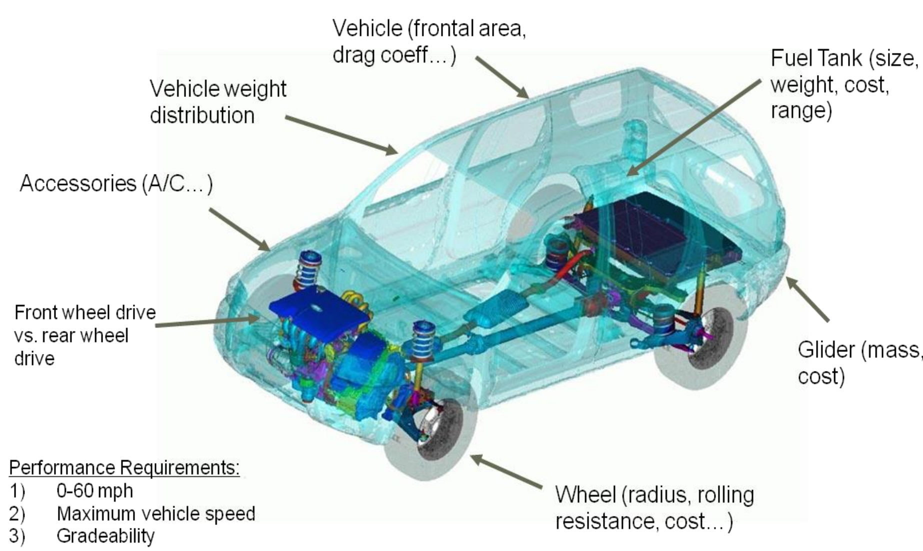


Figure 22 - Main vehicle assumptions

When available, the high-case assumptions were based on the FreedomCAR and Fuel Partnership program goals (Ward 2010). The other assumptions were developed through discussions with experts from companies, universities, and the national laboratories.

3.1. ENGINE

3.1.1. REFERENCE ENGINE AND PROJECTIONS

Several state-of-the-art internal combustion engines (ICEs) were selected as the baseline for the fuels considered: gasoline (spark ignition [SI]), diesel (compression ignition [CI]), ethanol (E85), and CNG. The engines used for HEVs and PHEVs are based on Atkinson cycles, generated from test data collected at Argonne's dynamometer testing facility (Bohn 2005). Table 1 shows the engines selected as a baseline for the study.

Table 1: Definition of the baseline engines used in the present study

Fuel	Source	Displacement (L)	Peak Power (kW)
SI (Conv)	Car manufacturer	2.4	123
CI	Car manufacturer	1.9	110
CNG	Car manufacturer	1.5	111
E85 (Conv)	Car manufacturer	2.2	106
SI/E85 (HEV)	Argonne	1.5	57

Technologies available to increase the efficiency of engines include the following:

- Low-friction lubricants
- Reduced engine friction losses
- Cylinder deactivation
- Variable valve timing (VVT) and variable valve lift
- Turbocharging and downsizing
- Variable compression ratio (VCR)
- Stoichiometric and lean-burn gasoline direct injection (GDI)
- Diesel engine

A literature review (Morrow et al. 2008) was conducted to select the preceding technologies and define their impacts on both peak efficiency and engine map. Since all the technologies could not be represented because of the lack of data, a few technologies were selected, including low-friction lubricants, reduced friction losses, direct injection, and VVT. Cylinder deactivation, turbocharging, and VCR were not included. It should be noted that several ongoing engine research projects could lead to technologies affording significantly higher fuel-efficiency gains than those considered in this study (Ciatti and Subramanian 2010). As such, the engine gains should be considered less aggressive than gains for other technologies and this should be taken into account during the analysis.

Figure 23 shows the peak efficiencies of the different fuels and technologies.

Among the different ICEs, the CNG engine shows the most significant efficiency increase, from 36% in the reference case to 52% in the 2045 high case, because of the introduction of direct injection. The other engines show a lower increase in efficiency, since they are already well-developed technologies. The efficiencies of the other ICEs increase from 42% in the reference case to 50% in the 2045 high case (diesel), 36% to 50% (gasoline), and 36% to 52% (ethanol for HEV and PHEV applications). Of note is that the difference in peak efficiency between gasoline and diesel is expected to narrow in the future, because of the combination of advanced gasoline engine technologies and the impact of evermore stringent after-treatments for diesel.

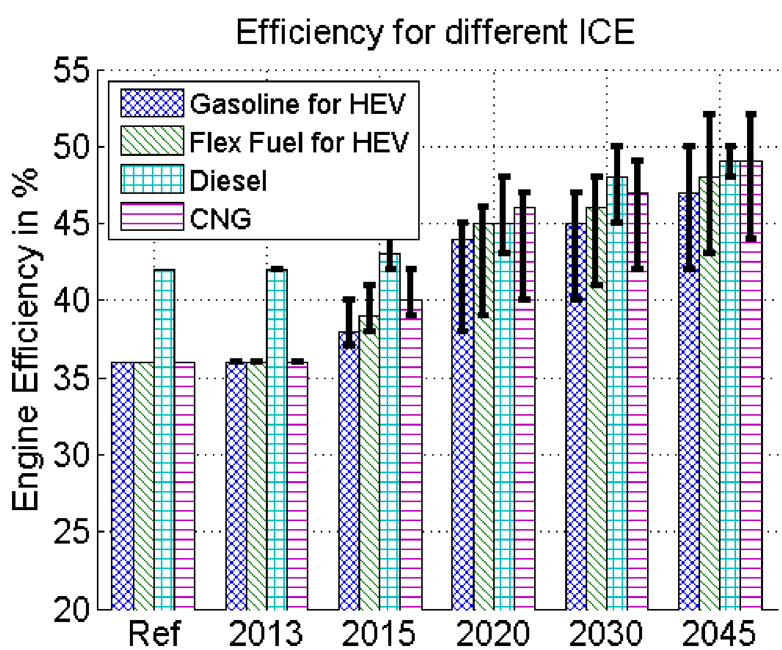


Figure 23 - ICE efficiency for diesel, CNG, and gasoline fuels

3.1.2. DETERMINATION OF NUMBER OF CYLINDERS

To properly select the reference engine and calculate its cost, it is necessary to decide how many cylinders are needed for a given power.

Figure 24 shows the relationship between the number of cylinders in a gasoline engine and the peak power. This figure is based on data in the literature. On the basis of Figure 24, 4-cylinder engines were used up to a power of 140 kW, 6-cylinder engines for a power between 140 and 220 kW, and 8-cylinder engines for a power above 220 kW.

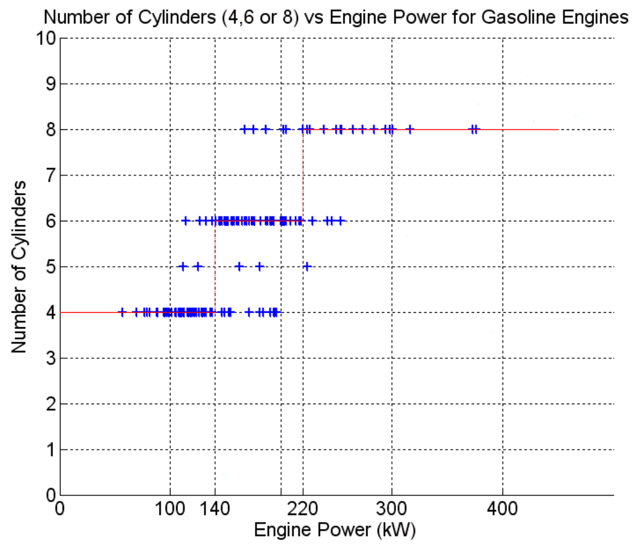


Figure 24 - Number of cylinders versus engine power for database gasoline engines (Blue = values from the database; red = thresholds chosen for the study.)

The same approach was taken for diesel engines, as shown in Figure 25. The small number of diesel engines in the U.S. database does not provide as clear a distribution as the gasoline case, but from the distribution shown in Figure 24, the same thresholds were used. The ethanol engines will use the same cylinder/engine-power equation as the gasoline and the diesel engines.

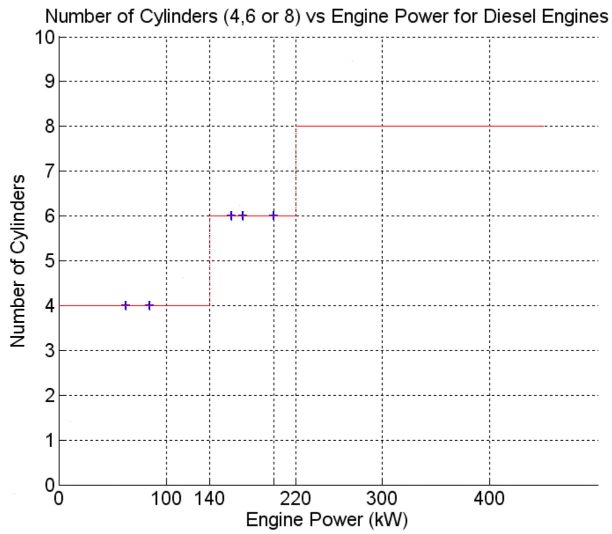


Figure 25 - Number of cylinders versus engine power for database diesel engines (Blue = values from the database; red = thresholds chosen for the study.)

3.2. FUEL-CELL SYSTEM

Fuel-cell vehicles are undergoing extensive R&D because of their potential for high efficiency and low emissions (zero-emission). Because fuel-cell vehicles remain expensive and there is limited demand for hydrogen at present, very few fueling stations are being built. To try to accelerate the development of a hydrogen economy, some OEMs in the automotive industry have been working on a hydrogen-fueled ICE as an intermediate step.

Figure 26 shows the specific power and specific energy of the fuel-cell system. As shown, the specific power and power density continuously increase. Between the reference case and 2045, the specific power increases by 67% to 120%, and the power density increases by 68% to 192%. It should be noted that in the case of the fuel-cell systems, all the assumptions other than the efficiency curve were provided by DOE.

The fuel-cell system model used for the study was based on a steady-state look-up table. The efficiency curve was provided by a car manufacturer. As a result, the additional losses from the balance of plant due to transient operating conditions were not taken into account.

Figure 27 shows the evolution of the fuel-cell system peak efficiencies. The peak fuel-cell efficiency was assumed to be at 60% currently and it will increase up to 68% by 2045.

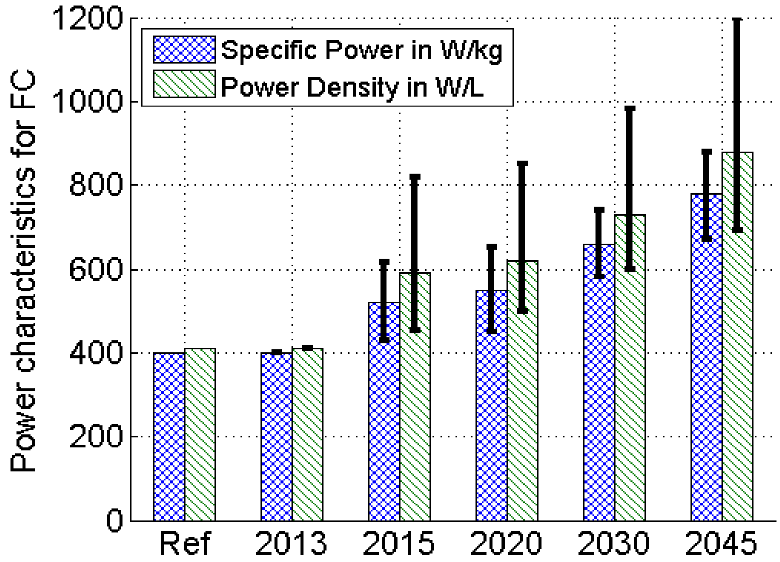


Figure 26 - Specific power and power density for fuel cell system

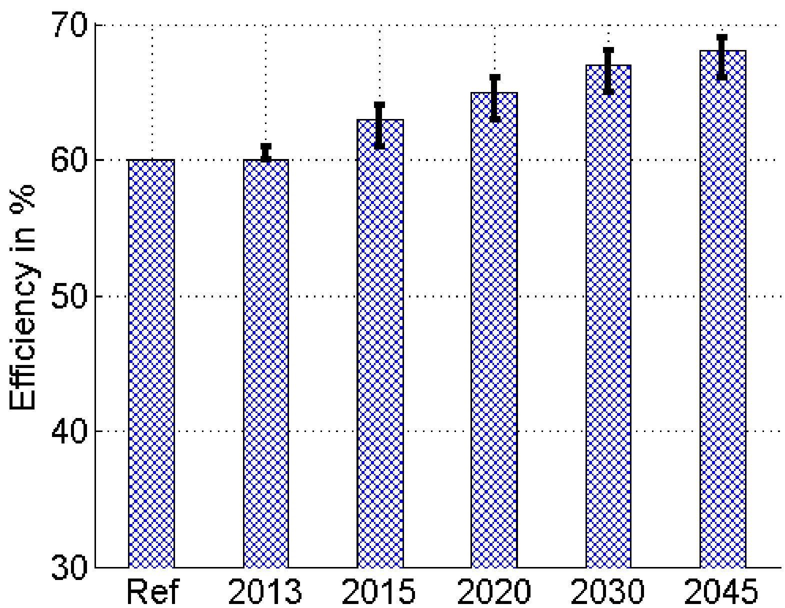


Figure 27 - Fuel-cell system efficiency and cost

3.3. ELECTRIC MACHINE

Two different electric machines were used as references in this study:

- Power-split vehicles operate with a permanent-magnet electric machine (similar to that used in the Toyota Camry) with a peak efficiency of 95%.

- Series configurations (both engine and fuel cell) and EVs use an induction primary electric machine with a peak efficiency of 95%.

The reference electric-machine data were provided by car companies, suppliers, and Oak Ridge National Laboratory.

As shown in Figure 28, the power-electronic specific power will significantly increase between 2013 and 2045. Both electric machines used in the study have a reference peak efficiency of 89%. As shown in Figure 29, it will increase from 89% to 98% between 2013 and 2030 and will remain at that value in 2045.

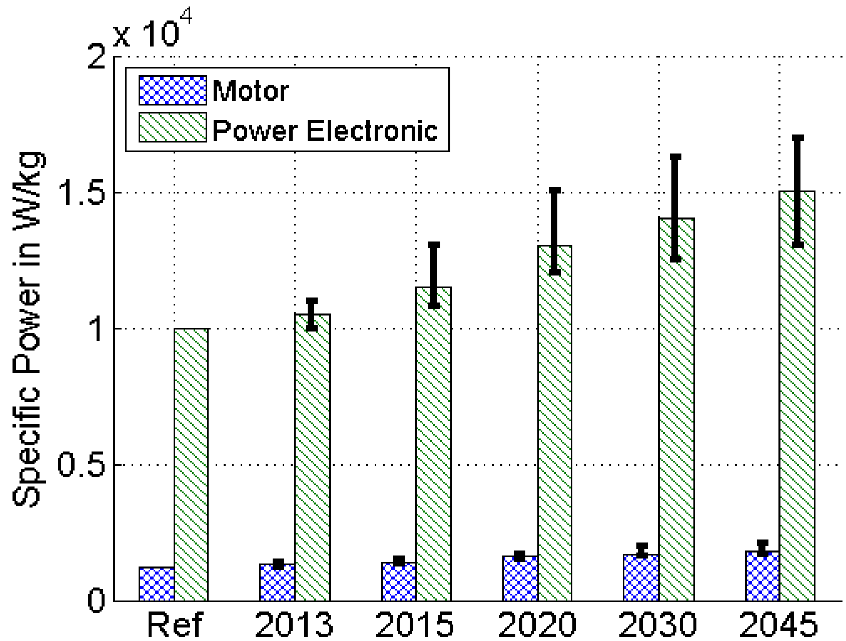


Figure 28 - Electric-machine and power-electronic specific power

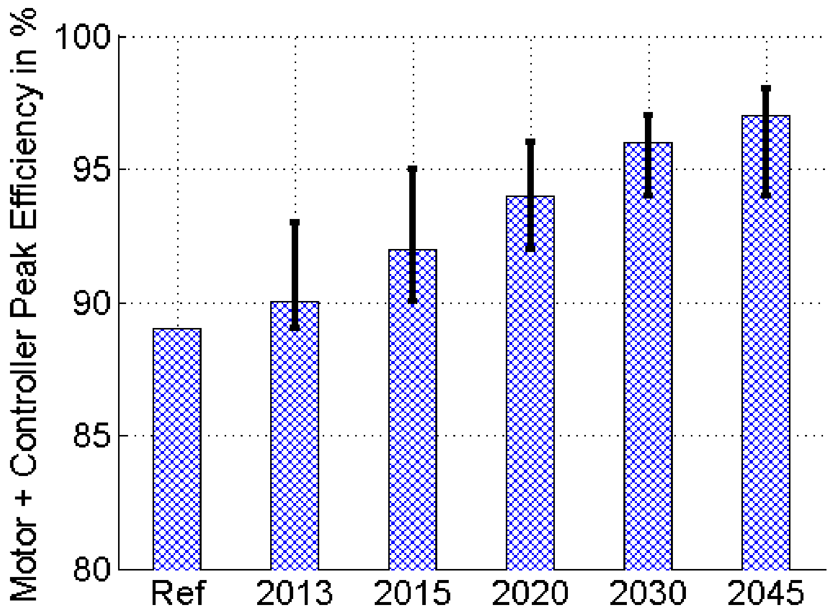


Figure 29 - Electric-machine peak efficiency

3.4. ENERGY STORAGE SYSTEM

Only batteries were used in the present study, on the assumption that ultra-capacitors alone could not provide sufficient available energy for full hybrid applications. We also considered that coupling ultra-capacitors with batteries would be cost prohibitive and that Li-ion battery life would be significantly improved in the short term, making the combination ineffective.

The batteries used in the study as the reference were provided by Argonne, Idaho National Laboratory, and major battery suppliers. A scaling algorithm developed by Argonne's battery experts was used for the high-energy cases (Nelson et al. 2007).

The battery used for the HEV reference case was a NiMH battery. It was assumed that this technology is the most likely to be used until 2015. This is why we simulated the HEVs with this battery for the reference case; 2013 low, average, and high cases. The model used was similar to the one found in the Toyota Prius. For PHEV applications, all the vehicles were run with a Li-ion battery from Argonne. Tables 2 and 3 provide summaries of the battery characteristics and technologies, respectively.

Table 2: Description of reference battery characteristics

	Source	Technology	Reference Cell Capacity [Ah]
HEV	Idaho National Laboratory	NiMH	6.5

	Battery manufacturer	Li-ion	6
PHEV	Argonne National Laboratory	Li-ion	41

Table 3: Battery technology selection for each timeframe

	2013			2015 to 2045		
	ref/low	**avg**	**avg**	**low**	**avg**	**high**
HEV	NiMH	NiMH	Li-ion	Li-ion		

After a long period of time, batteries lose some of their power and energy capacity. To be able to maintain the same performance at the end of life (EOL) compared with the beginning of life (BOL), an oversize factor is applied while sizing the batteries for both power and energy. These factors are supposed to represent the percentage of power and energy that will not be provided by the battery at the EOL compared with the initial power and energy given by the manufacturer. The oversize factor is decreased over time to reflect an improvement in the ability of batteries to uniformly deliver the same performance throughout their life cycles. Figure 30 shows that the reference vehicles are sized with a 20% power oversize factor for all hybrid vehicles and energy oversize factors of 30% for PHEVs. In 2045, these values will be reduced to 10% to 14% for power oversize, and 20% to 30% for PHEV energy oversize. These oversizing factors influence the cost and weight; however, all the simulations are run at EOL (i.e., the additional weight is taken into account, but the power and energy used for the simulation are the ones from EOL).

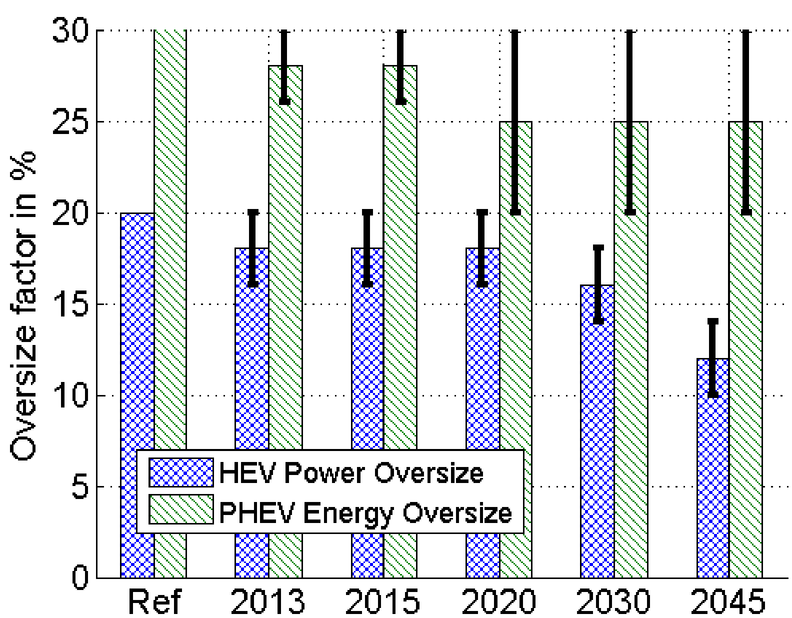


Figure 30 - Power and energy oversize for HEVs and PHEVs

Figures 31 and 32 show the relationship between the power/energy ratio and the battery energy cost.

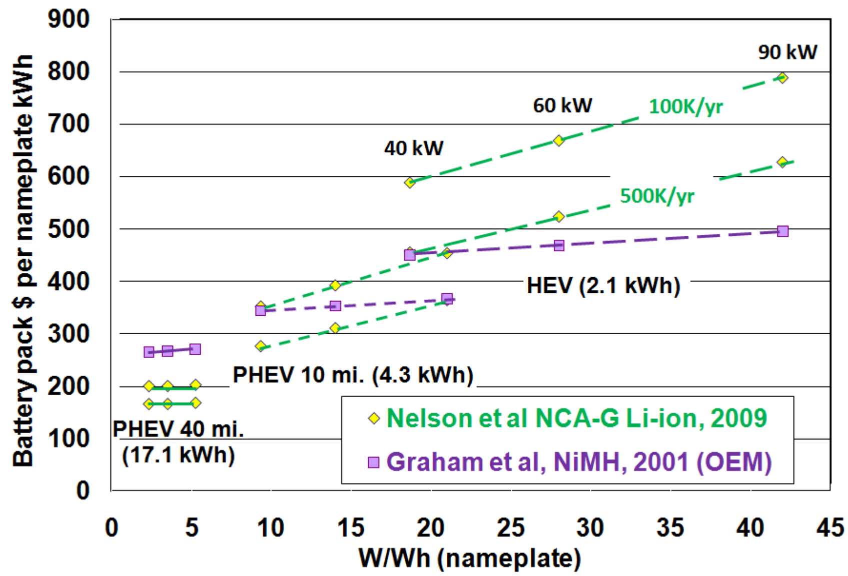


Figure 31 - Battery energy cost

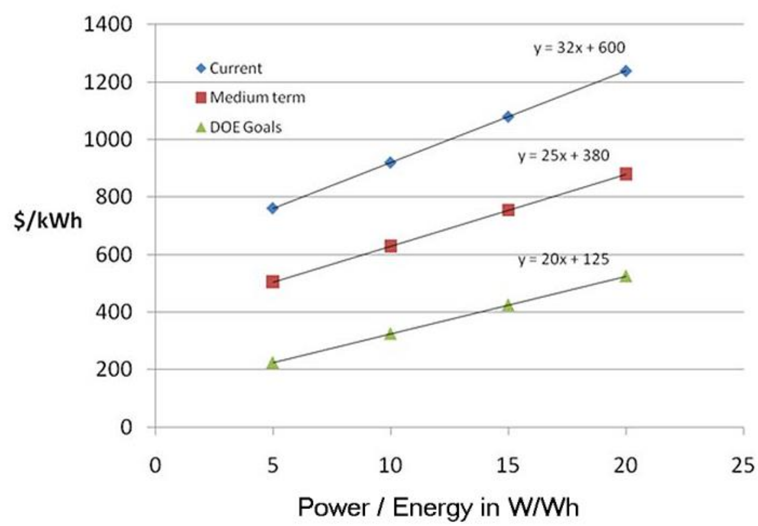


Figure 32 - Relation between power/energy ratio and battery energy cost

Figure 33 shows that the SOC values used for PHEVs were 30% for the minimum and 90% for the maximum in the reference case. It also shows that they change slightly over time to reach 20% for the minimum and 95% for the maximum in the 2045 high case.

Figure 34 shows that the SOC values used for EVs were 20% for the minimum and 90% for the maximum in the reference case. It also shows that they change slightly over time to reach 10% for the minimum and 95% for the maximum in the 2045 high case.

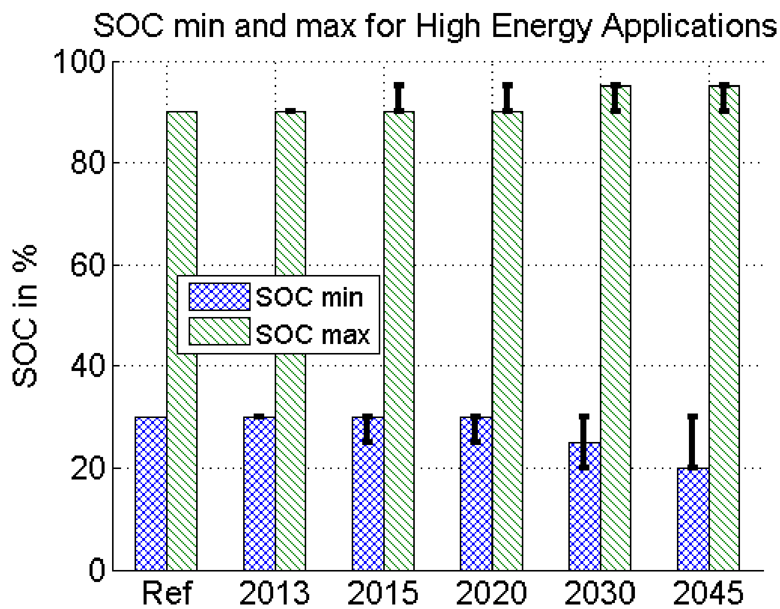


Figure 33 - Battery SOC for PHEVs

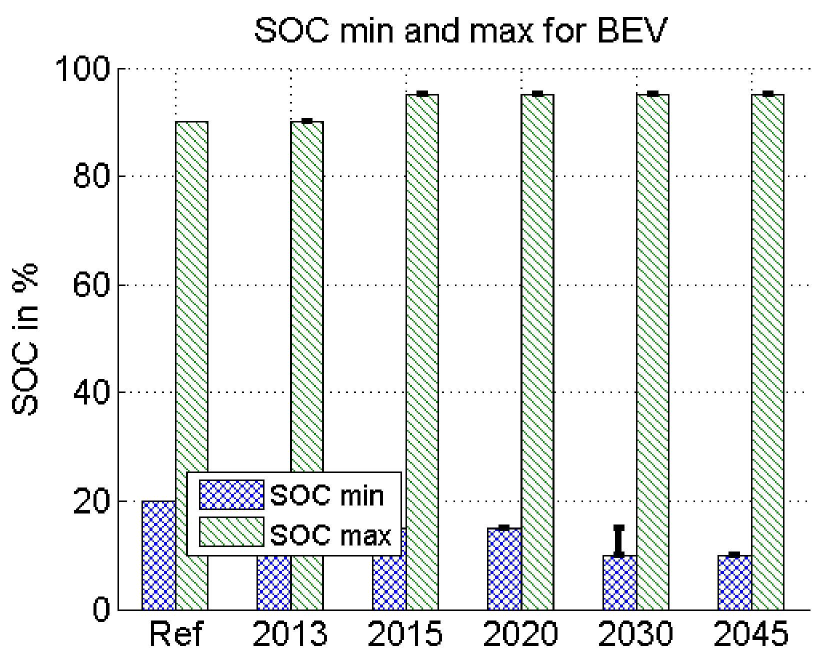


Figure 34 - Battery SOC for EVs

3.5. DRIVELINE

Several types of transmission technologies were considered in this study:

- **Increased number of gears for automatic transmissions.** Additional gears allow the engine to be operated closer to its best efficiency line. While they are now limited to high-end vehicles, high-speed transmissions (i.e., up to eight gears) are expected to be used in a larger number of vehicles in the near future.
- **Dual-clutch transmission (DCT).** Every car manufacturer, if it does not already have some DCT models in production, is working on developing the technology. DCTs are likely to be the next dominant transmission technology in the future, since they combine the advantages of automatic transmissions (drive quality—no torque interruption) and manual transmissions (efficiency—no torque converter).

Because of drive-quality requirements in North America, automated manual transmissions were not included in this study. Continuously variable transmissions have issues related to reliability and fuel-efficiency gains (the engine gains are often offset by higher transmission losses) and were not considered either.

Conventional vehicles were simulated with an automatic transmission, since that option best represents the American car market. However, a midsize car with a DCT was simulated for a few timeframes.

Power-split HEVs and PHEVs both have a planetary gear set with 78 ring teeth and 30 sun teeth. Finally, the fuel-cell vehicles and EVs use a two-speed manual transmission to increase the powertrain efficiency as well as allow them to achieve a maximum vehicle speed of at least 100 mph. Tables 4 through 7 give the characteristics of all transmissions used in the study.

Table 4: Transmission technologies modeled for different vehicle classes (*)

Parameter	2013			2015			2020			2030			2045		
	Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High
Peak Efficiency (%)															
Automatic Trans	97	97.5	98	97	98	98.5	97.5	98	98.5	97.5	98	98.5	97.5	98	98.5
DCT	98.5	98.5	98.5	98.5	98.5	99	98.5	98.5	99	98.5	98.5	99	98.5	98.5	99
Planetary gearset	98	98	99	98	98.5	99	98	98.5	99	98	98.5	99	98	98.5	99
Final Drive Peak Efficiency (%)	98	98	98	98	98	98.5	98	98	98.5	98	98	98.5	98	98	98.5
Conventional Vehicle															
gb Compact	MCOM6	MCOM6	MCOM6	MCOM6	MCOM6	MCOM6	MCOM6	MCOM6D	MCOM8D	MCOM6D	MCOM8D	MCOM8D	MCOM6D	MCOM8D	MCOM8D
gb Midsize	MCAR6	MCAR6	MCAR6D	MCAR6	MCAR6	MCAR6D	MCAR6	MCAR8	MCAR8D	MCAR8	MCAR8	MCAR8D	MCAR8	MCAR8D	MCAR8D
gb Small_SUV	SSUV6	SSUV6	SSUV6D	SSUV6	SSUV6	SSUV6D	SSUV6	SSUV6D	SSUV8D	SSUV6D	SSUV6D	SSUV8D	SSUV6D	SSUV8D	SSUV8D
gb Midsize_SUV	MSUV6	MSUV6	MSUV6	MSUV5	MSUV6	MSUV6	MSUV6	MSUV6	MSUV7	MSUV6	MSUV7	MSUV8	MSUV7	MSUV8	MSUV8
gb Pickup	PICKUP5	PICKUP5	PICKUP5	PICKUP5	PICKUP6	PICKUP6	PICKUP6	PICKUP6	PICKUP8	PICKUP6	PICKUP8	PICKUP8	PICKUP8	PICKUP8	PICKUP8

(*) The code names of the transmissions are based on the vehicle class (i.e., COM for midsize, MCAR for midsize car) and the number of gears. For example, SSUV6 means a small SUV with a six-gear transmission.

Table 5: Gear ratios, final drive, and cost for all transmissions

	Name	Type									
Compact car	MCOM5	AU	Gear Ratios	3.67	2.14	1.45	1.03	0.81			
			Final Drive	3.08							
	MCOM6	AU	Gear Ratios	4.45	2.91	1.89	1.44	1	0.74		
			Final Drive	3.47							
	MCOM6D	DCT	Gear Ratios	3.917	2.429	1.436	1.021	0.867	0.702		
			Final Drive	3.85							
	MCOM8D	DCT	Gear Ratios	4.6	2.72	1.86	1.46	1.23	1	0.82	0.69
			Final Drive	3.06							
Midsize CAR	MCAR5	AU	Gear Ratios	2.65	1.52	1.04	0.74	0.54			
			Final Drive	4.44							
	MCAR6	AU	Gear Ratios	4.58	2.91	1.91	1.44	1	0.74		
			Final Drive	3.2							
	MCAR6D	DCT	Gear Ratios	3.45	1.84	1.31	1.03	0.84	0.68		
			Final Drive	4.38							
	MCAR8	AU	Gear Ratios	4.71	3.14	2.1	1.67	1.29	1	0.84	0.67
			Final Drive	3.06							
	MCAR8D	DCT	Gear Ratios	4.6	2.72	1.86	1.46	1.23	1	0.82	0.69
			Final Drive	3.06							
Small SUV	SSUV5	AU	Gear Ratios	4.24	2.36	1.52	1.05	0.76			
			Final Drive	3.43							
	SSUV6	AU	Gear Ratios	4.58	2.96	1.91	1.44	1	0.75		
			Final Drive	3.51							
	SSUV6D	DCT	Gear Ratios	4.48	2.87	1.84	1.41	1	0.74		
			Final Drive	3.16							
	SSUV8D	DCT	Gear Ratios	4.6	2.72	1.86	1.46	1.23	1	0.82	0.69
			Final Drive	3.06							
Midsize SUV	MSUV5	AU	Gear Ratios	3.22	2.32	1.55	1	0.71			
			Final Drive	3.25							
	MSUV6	AU	Gear Ratios	4.15	2.34	1.52	1.14	0.86	0.69		
			Final Drive	2.52							
	MSUV7	AU	Gear Ratios	4.92	3.19	2.04	1.41	1	0.862	0.771	
			Final Drive	3.35							
	MSUV8	AU	Gear Ratios	4.71	3.14	2.1	1.66	1.28	1	0.83	0.66
			Final Drive	3.72							
Pickup Truck	45RFE	AU	Gear Ratios	3	1.67	1	0.75				
			Final Drive	3.55							
	PICKUP5	AU	Gear Ratios	3.52	2.042	1.4	1	0.716			
			Final Drive	3.9							
	PICKUP6	AU	Gear Ratios	4.17	2.34	1.52	1.14	0.86	0.69		
			Final Drive	2.17							
	PICKUP8	AU	Gear Ratios	4.696	3.13	2.104	1.667	1.285	1	0.839	0.667

Table 6: Power-split transmission characteristics for all vehicle classes

Cost	840
Gear Ratios	Sun number of teeth = 30. Ring number of teeth = 78
Final Drive	4.059

Table 7: Fuel-cell and electric-vehicle transmission characteristics for all vehicle classes

Cost	840
Gear Ratios	1.86/1
Final Drive	4.44

The efficiencies of the transmission types, other than automatic, and of the final drive, are already very high and will increase only slightly over time, as shown in Figure 35. The planetary gear set will have the best efficiency in 2030 and 2045 and will constitute the high case, with 99% efficiency.

The shifting algorithm that was used automatically defines the shifting strategy based on the powertrain ratios and the component efficiencies to minimize fuel consumption while maintaining acceptable drive quality (i.e. torque reserve). The algorithm has been validated using APRF test data, with several conventional vehicles over the past 10 years.

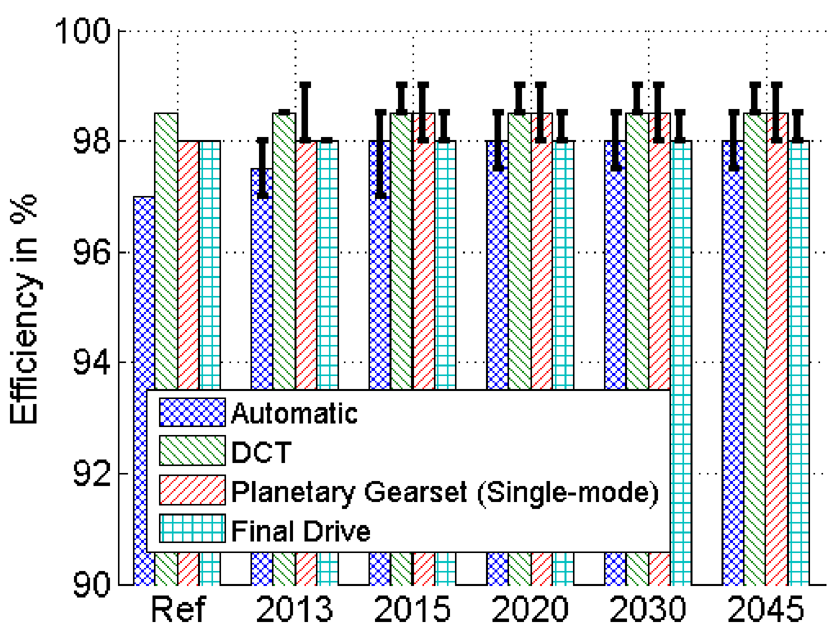


Figure 35 - Transmission peak efficiencies

3.6. BODY AND VEHICLE

3.6.1. TECHNOLOGY OVERVIEW

One of the main factors affecting fuel consumption is vehicle weight. Lowering the weight ("lightweighting") reduces the forces required to follow the vehicle speed trace. As a result, the components can be downsized, resulting in smaller components and decreased fuel consumption. However, the impact of lightweighting is not the same for all the powertrain configurations. Studies show that the technology has greater influence in conventional vehicles than their electric-drive counterparts (Pagerit et al. 2006).

The principal methodologies include material substitution (i.e., high-strength low-alloy steel, aluminum, magnesium, etc.), improved packaging (i.e., ratio of interior volume to exterior size and weight), and unit body construction (i.e., elimination of conventional chassis/body structure). Several studies have shown the potential to decrease the weight by as much as 20% without cost penalties, which highlights the great potential of the technology (USCAR 2010).

Reductions in rolling resistance, frontal area, and drag coefficient also have the potential to significantly improve fuel consumption as they also lead to a reduction in the force required at the wheel. In this study, the assumption was that the frontal area will increase rather than decrease because American consumers have demanded vehicles with greater passenger and cargo volume (i.e., more room inside the vehicle).

Table 8 gives the main characteristics used as a reference.

Table 8: Main characteristics of the different vehicle classes

	Glider Mass (Ref) in kg	**Frontal Area (Ref) in m²**	**Tire**	**Wheel Radius in m**
Compact	820	2.19	P195/65/R15	0.317
Midsize	1,000	2.24	P195/65/R15	0.317
Small SUV	1,150	2.57	P225/75/R15	0.359
Midsize SUV	1,260	2.93	P235/70/R16	0.367
Pickup	1,500	3.27	P255/65/R17	0.381

3.6.2. LIGHTWEIGHTING

The same glider mass reduction factor was applied to all vehicle classes (Figure 36).

The glider mass will be linearly reduced by up to 52% in the 2045 high case relative to the reference case. The reduction is due to the use of different materials and technologies like aluminum. Note that the mass reduction of the glider has been separated into three sections: body mass, chassis mass, and rest of weight. First, the glider weight in this study was considered as the vehicle weight minus the powertrain components; that is, the engine, after-treatment, electric machines, fuel cell, fuel storage, energy storage system, transmission, final drive, wheels, and accessories. A fixed percentage of the glider mass was used for each section. It was assumed that 44% of the glider is due to its body weight, 26% to its chassis weight, and 30% to other components (e.g., seats).

The glider cost changes are due to the technologies used to achieve the glider mass reduction (Figure 37). For a midsize car, the reference-case glider costs $9,955 and is steel unibody.

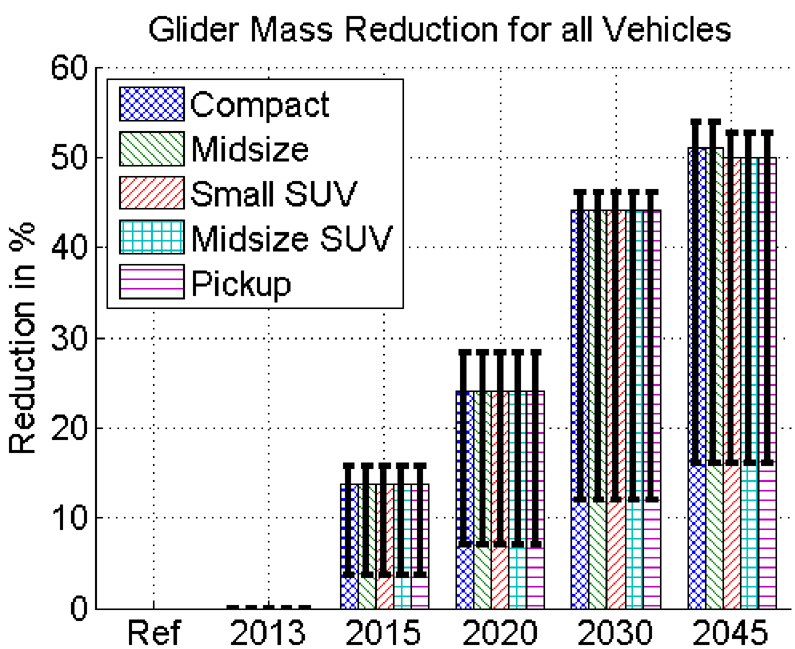


Figure 36 - Glider mass reduction for all vehicle classes

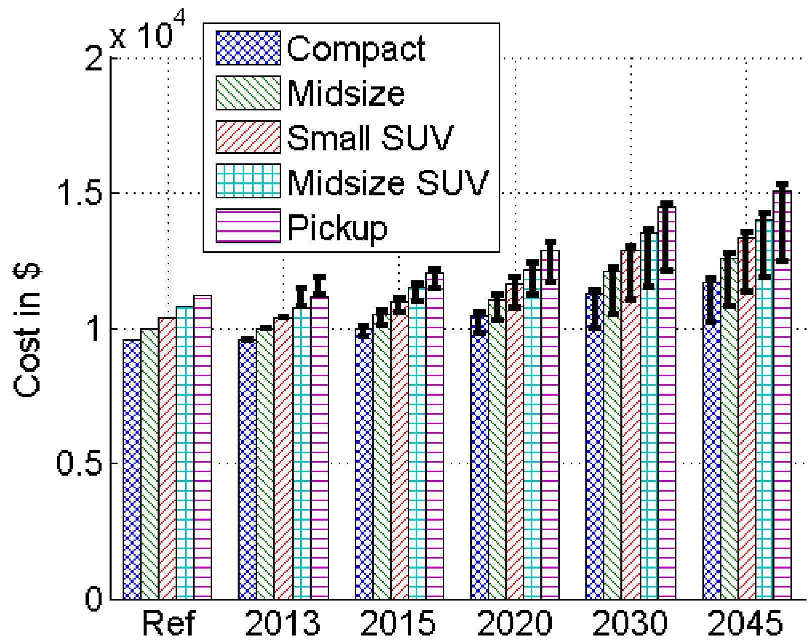


Figure 37 - Glider costs for the five vehicle classes

3.6.3. DRAG COEFFICIENT AND ROLLING RESISTANCE

The same frontal-area increase factor was applied to all vehicle classes (Figure 38). The frontal area is expected to increase up to 6% in the 2045 low case relative to the reference case. The increase pattern is not the same between cases. Whereas the average and low cases will continuously increase, the high-case increase will be maintained at 0% until 2015 and will be at 2% for the rest of the timeframes.

As shown in Figure 39, the drag coefficient and rolling resistance show similar evolutions across vehicle classes.

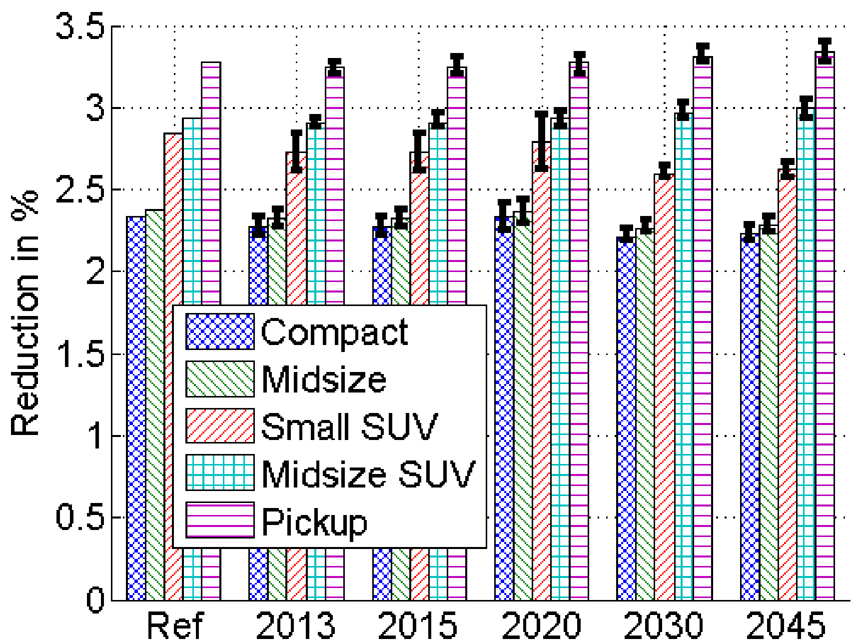


Figure 38 - Frontal-area percentage increase over reference for all vehicle classes

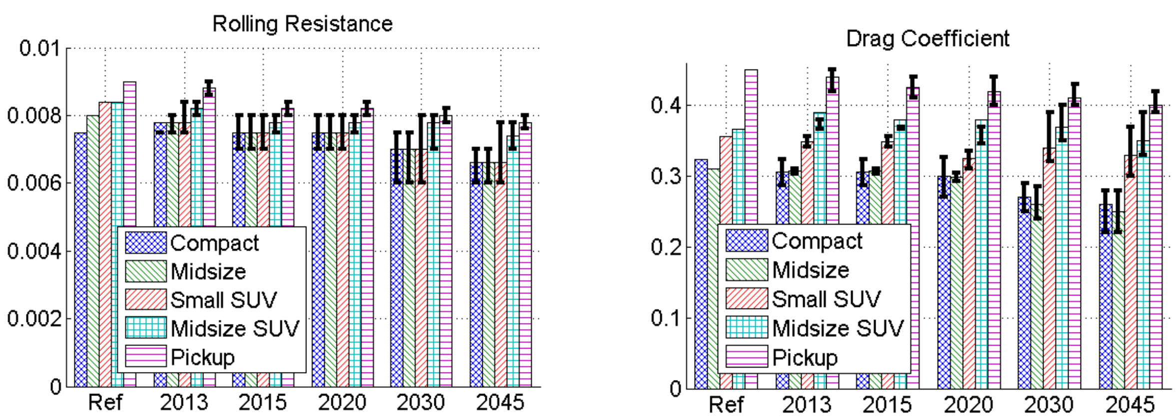


Figure 39 - Drag coefficient (right) and rolling resistance (left) values for the five vehicle classes

3.6.4. ACCESSORIES

As shown in Figure 40, the accessory load is expected to increase over time as the power needed to supply electrical and electronic components increases in accordance with customers' expectations (e.g., global positioning system [GPS]) and powertrain complexity (e.g., added controllers). However, in all timeframes, the non-conventional powertrains generally consume less power, except in the high cases. The values shown in

Figure 40 are representative of average consumption during the standard cycle testing (i.e., dynamometer test). Real-world accessory consumption would be higher.

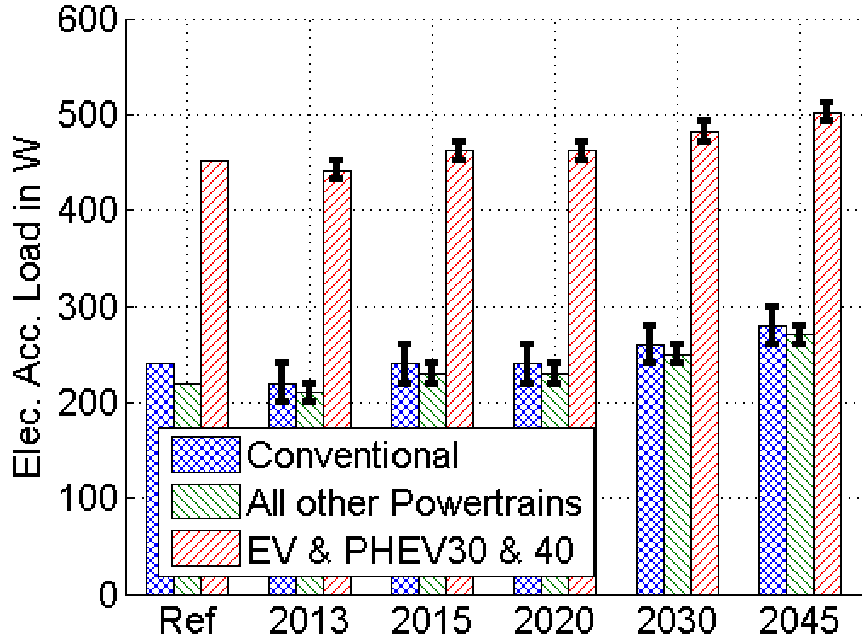


Figure 40 - Electrical accessory load

4. POWERTRAIN SELECTION

As discussed previously, hundreds of powertrain options are possible. The following powertrains were selected for the EDVs:

- Single mode power-split hybrid with fixed gear ratio (HEV, PHEV10, PHEV20)
- Series engine with two-speed gearbox (PHEV30, PHEV40)
- Series fuel cell with two-speed gearbox (HEV, PHEVs)
- Electric drive with two-speed gearbox for BEV

The selection of the single-mode power-split hybrid was based on the current sales volume of both Toyota and Ford hybrid vehicles, which makes that configuration the dominant one on the market. However, multi-mode configurations, such as the one implemented in the GM Tahoe (Grewe et al. 2007), are interesting options, especially for SUV applications (Kim et al. 2010), and will be added in future studies.

The series engine configuration selected is the simplest one and has been used by many companies. For this option, the E-REV powertrain used in the GM Volt (Tate and Savagian 2009) offers significant advantages, especially during high-vehicle-speed operations. Since the Volt configuration was not yet public at the beginning of this project, it was not used but will be added in future updates.

All the vehicles driven solely by electrical power use a two-speed gearbox. This choice was made to reach the vehicle maximum-speed requirement of at least 100 mph. This transmission also allows an increase in the powertrain efficiency. Another option to improve the electrical consumption is to use two electric machines (as is the case in the GM Volt); however, the multi-speed option was preferred in order to meet the vehicle maximum-speed requirements.

This study will be regularly updated, and the authors are planning to use both the multi-mode transmission and E-REV configurations in future work. A significant amount of work has already been done with the two-mode hybrid as the powertrain, and vehicle-level controls have been developed and validated using vehicle test data from the APRF at Argonne (Kim et al. 2009; Karbowski et al. 2010). Models of the E-REV, as well as its preliminary vehicle-level energy management, have also been developed and will be validated in the future.

5. VEHICLE-LEVEL CONTROL STRATEGIES

It is easy to create a bad HEV, fuel-cell vehicle, and so forth, if all one is doing is assembling the various parts. It takes significant knowledge, however, to design one that meets all customers' expectations, from performance to fuel consumption and drive quality. The vehicle-level control strategies used for the powertrain described previously were developed over the past 12 years (Pasquier et al. 2001; Pagerit et al. 2005; Sharer et al. 2008; Cao 2007; Karbowski et al. 2006). Generic processes were developed over the years to not only create but also validate the vehicle-level control strategies.

Figure 41 shows the generic process developed by Argonne for energy management. The process is defined in three steps:

- Global Optimization (Karbowski et al. 2006): The objective of this step is to define the main rules. For example, the engine turns ON based on the battery SOC, vehicle speed, and wheel torque demand.
- Rule-Based Control: In this step, the rules previously defined are implemented into an algorithm (generally Simulink and StateFlow) and exercised to make sure they operate properly.
- Heuristic Optimization: The objective of the last step is to define the values of the parameters of the main control strategy. For example, at which wheel torque does the engine turn ON for a specific SOC? The algorithm Argonne generally uses to automatically define the parameters is DIRECT (DIvided RECTangles).

Other approaches, such as instantaneous optimizations (Karbowski et al. 2010) were also developed and implemented into Autonomie but were not used in the present study.

Argonne has several state-of-the-art vehicle dynamometers and has been involved in testing and developing test procedures for advanced vehicles for many years. Over the past 12 years, numerous vehicle configurations from different classes have been tested at the APRF. More than 20 of them were modeled and validated into the Powertrain System Analysis Toolkit (PSAT) and now Autonomie. These included conventional starter-alternators, full hybrids (input power-split, dual-mode power-split), plug-in hybrids (both after-market and manufacturer prototypes), and EVs. The vehicles were validated within 1% for the conventional vehicles, 2% for starter-alternators, and 5% for hybrids, which in all cases is within the test-to-test repeatability.

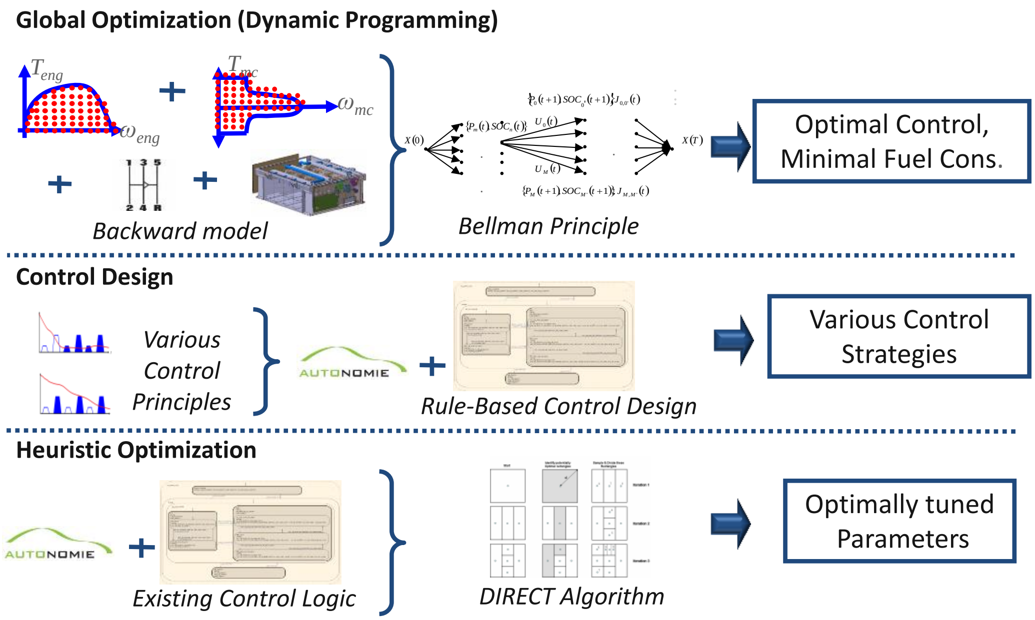


Figure 41 - Vehicle-level control strategy development

6. VEHICLE DEFINITION

6.1. VEHICLE TECHNICAL SPECIFICATIONS

All the vehicles were sized to meet the same requirements:

- Initial vehicle movement (IVM) to 60 mi/h in 9 sec +/-0.1 sec
- Maximum grade of 6% at 65 mi/h at gross vehicle weight (GVW)
- Maximum vehicle speed >100 mi/h

These requirements are a good representation of the current American automotive market as well as American drivers' expectations. A relationship between curb weight and GVW was developed based on current technologies.

6.2. SIZING ALGORITHMS

Because of the large number of vehicles (several thousand) and the diversity of powertrain options, it is not feasible to manually size each vehicle's components to match the performance targets. Some studies (Kromer and Heywood 2008) defined their vehicles by maintaining a constant P/W ratio between all powertrain configurations. Due to the impact of the component max torque shapes, maintaining a constant P/W ratio between all configurations leads to an inconsistent comparison between technologies because of different performances. Each vehicle should be sized independently to meet specific vehicle technical specifications.

Not properly sizing the components will lead to differences in both fuel consumption and cost and will influence the results. For example, the P/W ratio for a 2013 midsize vehicle with IVM = 60 mi/h in 9 sec varies from 85 to 75 W/kg, depending on the powertrain configuration. This difference will increase in the future because of a decrease in weight penalty for the electrified powertrains.

On this basis, we developed several automated sizing algorithms to provide a fair comparison between technologies. Different algorithms were defined depending on the powertrain (i.e., conventional, power-split, series, electric) and the application (i.e., HEV, PHEV).

All algorithms were based on the same concept: the vehicle is built from the bottom up, meaning each component assumption (i.e., specific power, efficiency, etc.) was taken into account to define the entire set of vehicle attributes (i.e., weight, etc.). This process is always iterative in the sense that the main component characteristics (i.e., maximum power, vehicle weight, etc.) are changed until all the VTS are met. On average, the algorithm takes between 5 and 10 iterations to converge. Figure 42 is an example of the iterative process for a conventional vehicle.

Since each powertrain and application is different, the rules were specific. For example:

- For HEVs, the electric-machine and battery powers were determined to capture all the regenerative energy from a UDDS cycle. The engine and the generator were then sized to meet the grade ability and performance (IVM; 60 mi/h) requirements.

- For PHEV10s and PHEV20s, the electric-machine and battery powers were sized to be able to follow the UDDS cycle in electric-only mode (this control was only used for the sizing; a blended approach was used to evaluate consumptions). The battery usable energy was defined to follow the UDDS drive cycle for 10 or 20 mi, depending on the requirements. The engine was then sized to meet both performance and grade ability requirements (usually, grade ability is the determining factor for PHEVs).

- For PHEV30s and PHEV40s, the main electric-machine and battery powers were sized to be able to follow the aggressive US06 drive cycle (duty cycle with aggressive highway driving) in electric- only mode. The battery usable energy was defined to follow the UDDS drive cycle for 30 or 40 mi, depending on the requirements. The genset (engine + generator) or the fuel-cell systems were sized to meet the grade ability requirements.

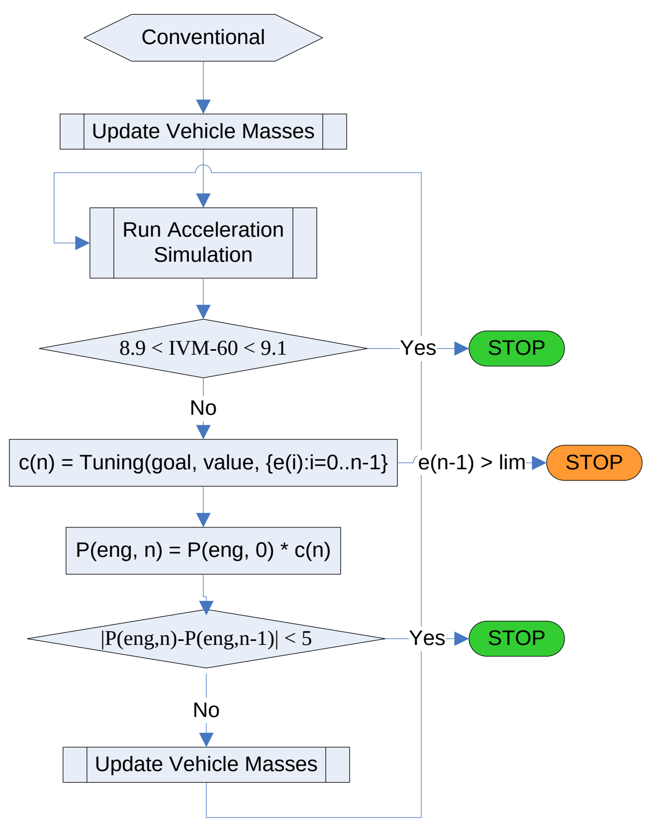


Figure 42 - Conventional powertrain sizing algorithm

It is important to note that the sizing algorithms provided the optimum component sizes when OEMs would have to select among the available choices.

6.3. SIZING RESULTS

This section describes the maximum power, energy, and weight of the different vehicles after sizing.

6.3.1. CONVENTIONAL POWERTRAIN

The component characteristics of each vehicle class evolve similarly. In the following section, to avoid presenting too many figures and plots, only the midsize class is presented.

Figure 43 shows the gasoline-engine peak power. One notices a small decrease in peak power due to lightweighting.

Figure 44 shows the peak power of the diesel, CNG, and ethanol engines compared with the gasoline engine. One notices that the diesel, CNG, and ethanol ratios stay roughly constant over time at around 0.9, indicating that technology improvements (e.g., weight reduction, aerodynamics) influence all engine technologies similarly with respect to engine peak efficiency.

Figure 45 shows that engine power changes linearly with vehicle weight. The fuel order tracks the power ratios previously described. All engine technologies cover the same mass range but do not require the same power; higher torque is present at lower engine speed in the diesel case.

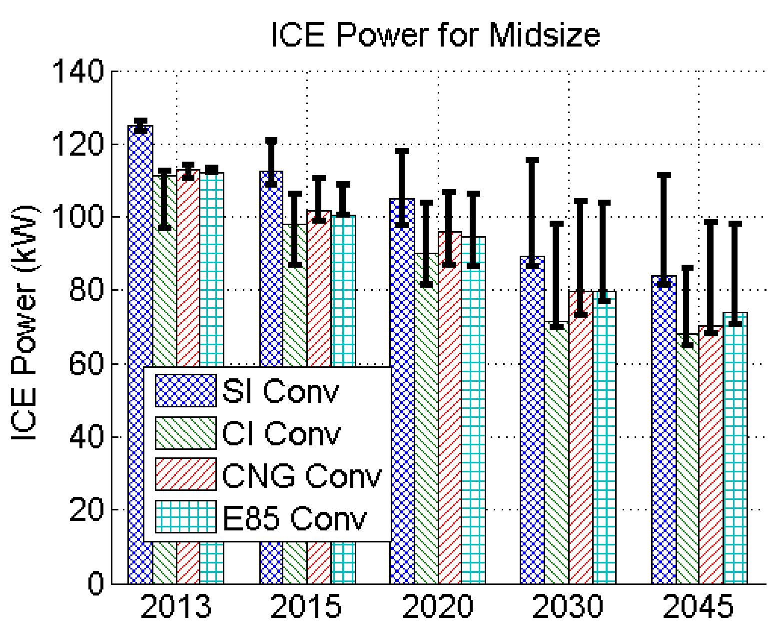


Figure 43 - Engine peak power with conventional powertrain for midsize car

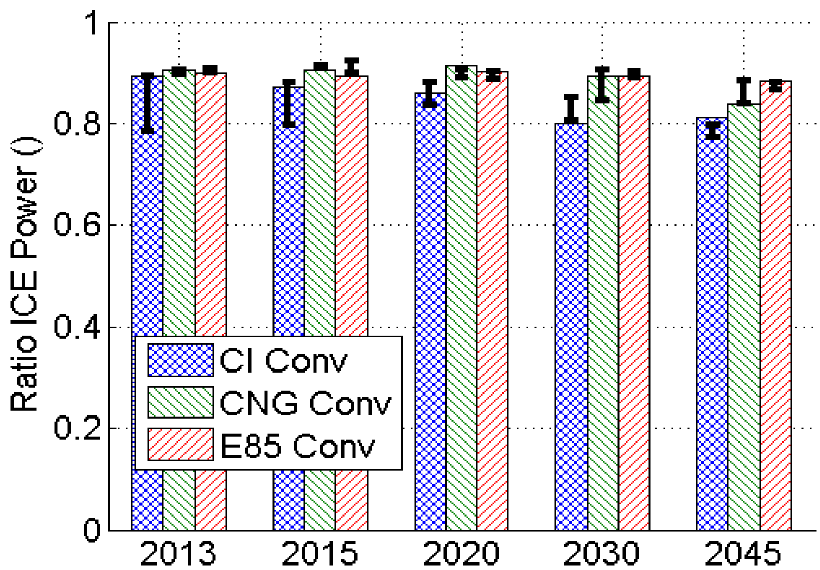


Figure 44 - Engine peak power compared with the same-year, same-case conventional gasoline engine for a midsize car

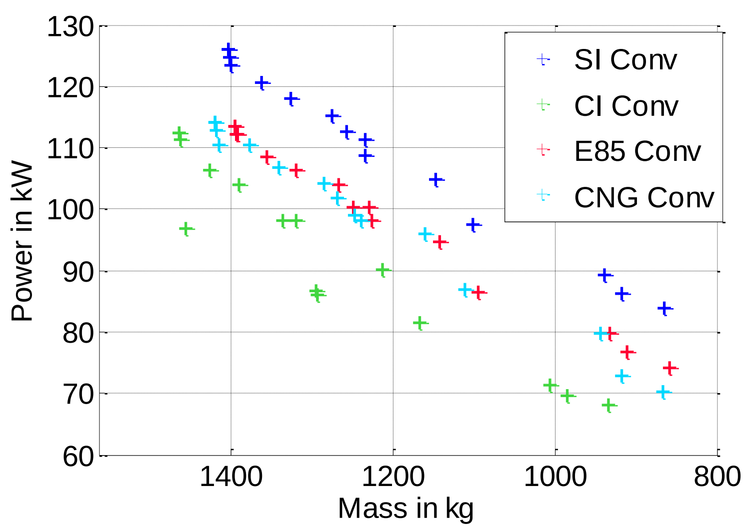


Figure 45 - Engine peak power as a function of vehicle mass for conventional gasoline engine

6.3.2. ENGINE HEV

ENGINE

Figure 46 shows the peak power for midsize HEVs with gasoline engines. The engine power for HEVs is determined by both the performance and grade requirements. While performance is the primary factor for current technologies, future lightweighting makes grade ability requirements critical for some cases.

The ICE peak-power ratios also stay roughly constant over time for the power-split HEVs (Figure 47). CNG and ethanol have approximately the same ratio over time, around 1, whereas diesel stays a little bit above 1. Engine sizes are comparable across fuels for HEVs over time, unlike conventional engines where using diesel, CNG, or ethanol fuels lead to engine downsizing.

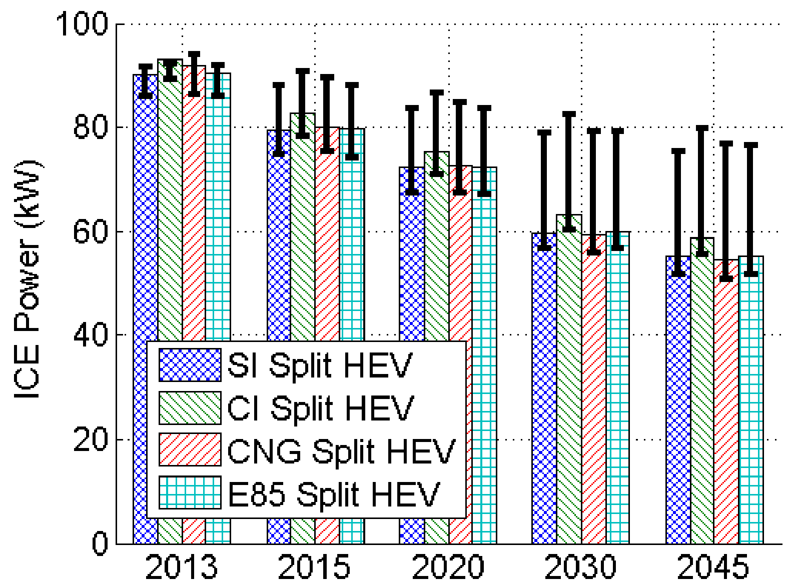


Figure 46 - Engine peak power for midsize HEVs with conventional powertrains

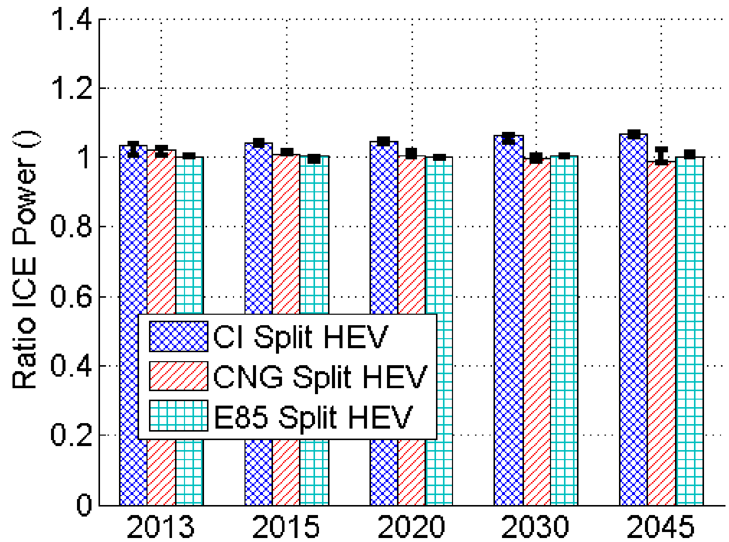


Figure 47 - Engine peak power compared with the same-year, same-case gasoline split-HEV engine for a midsize car

ELECTRIC MACHINE

Figure 48 shows the electric-machine power for HEVs with different fuels.

As shown in Figure 49, the peak-power ratios stay roughly constant over time. The diesel split HEV has a more powerful electric machine than the gasoline split HEV. However, the CNG split HEV electric machine is more powerful than the gasoline vehicle in 2013. For the ethanol vehicle, the electric-machine ratios are in the same range as the ICE power ratios.

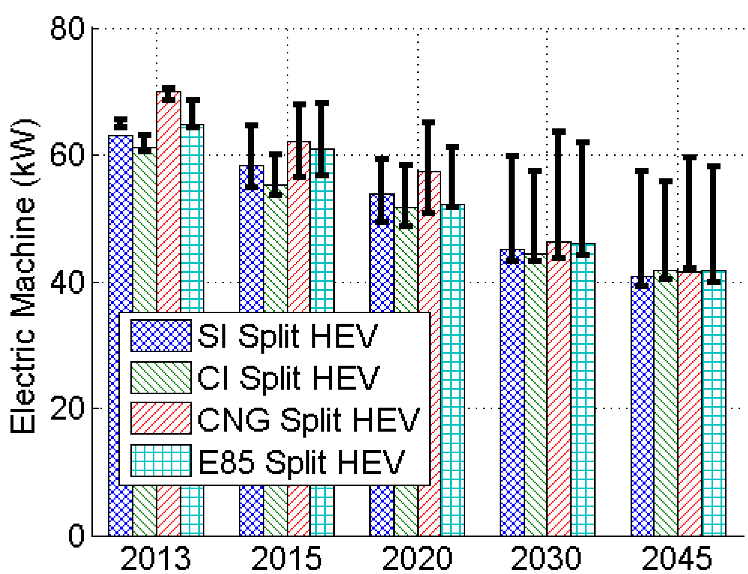


Figure 48 - Electric-machine power for midsize split HEVs

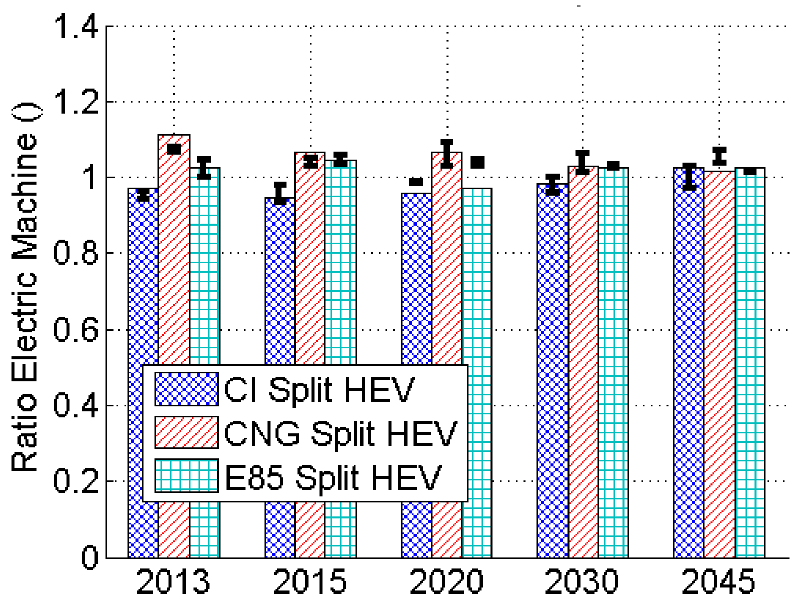


Figure 49 - Electric-machine peak power compared with the gasoline HEV engine for a midsize car

BATTERY

Figure 50 shows the HEV battery power. The powers were determined to capture the entire energy during deceleration on the UDDS drive cycle. Lightweighting and increased component efficiencies contribute to lower battery peak power.

Since the sizing algorithm for HEVs does not modify the battery capacity, the trend of the total energy follows the total power (Figure 51).

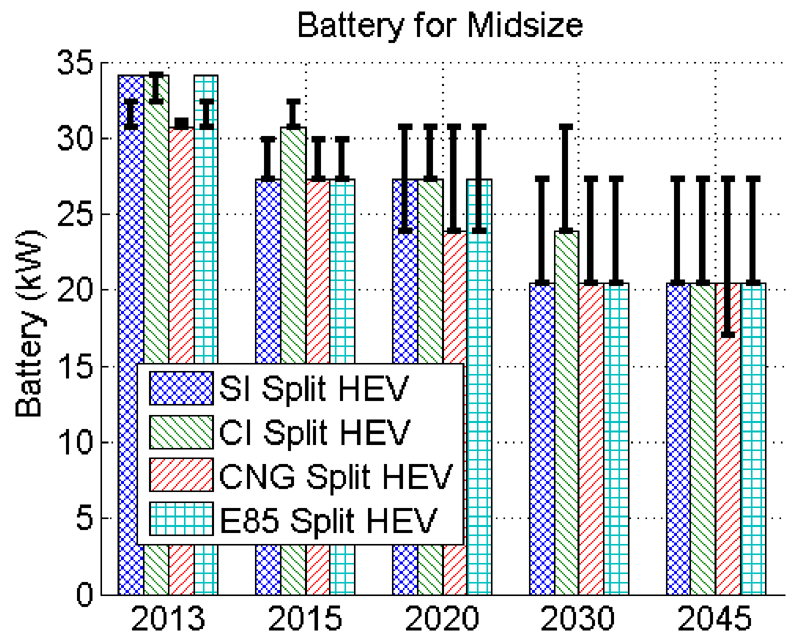


Figure 50 - Battery power for midsize gasoline HEVs

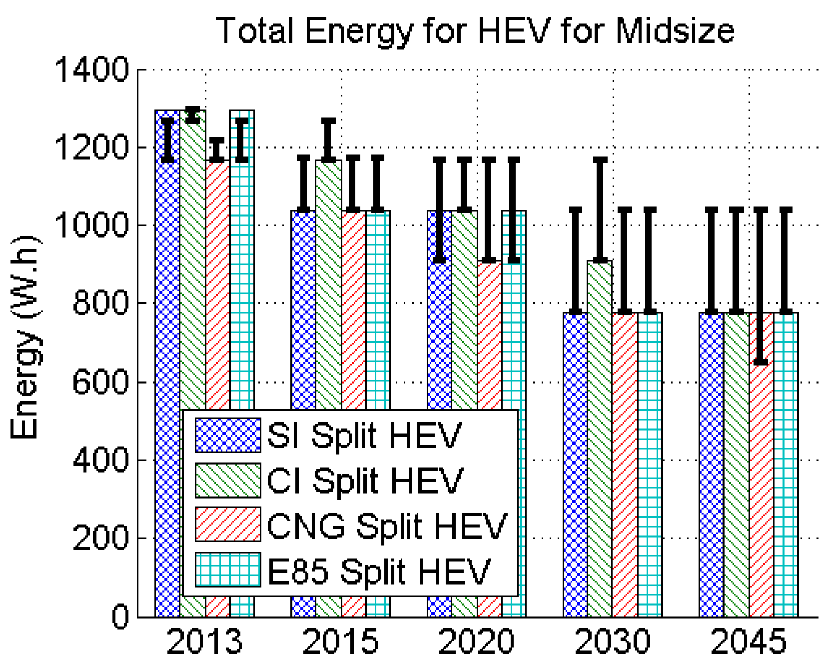


Figure 51 - Total battery energy for midsize HEVs

6.3.3. PHEV

ENGINE

Figure 52 shows the gasoline-engine peak power for the various PHEV powertrains and timeframes. In this case, because of the large electric machine, the engines were all sized to provide gradeability.

Across all the AERs for power-split PHEVs, Flex-Fuel engines have power similar to their gasoline counterparts, while diesel engines are the most powerful. The power ratios between the various engines and the gasoline engine (Figure 53) are stable over time and from one AER to another. The trends are similar for the PHEV30 and PHEV40.

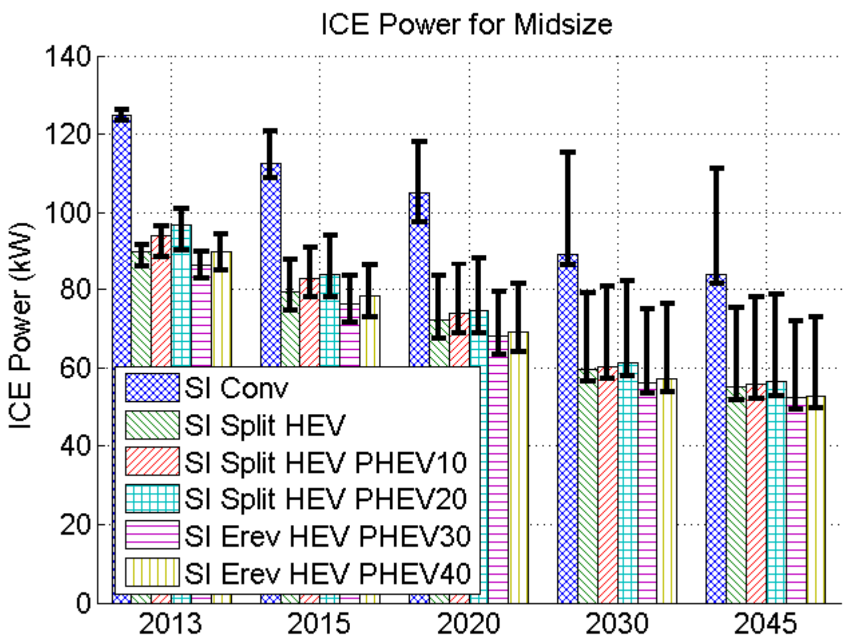


Figure 52 - Engine peak power for midsize PHEV powertrains

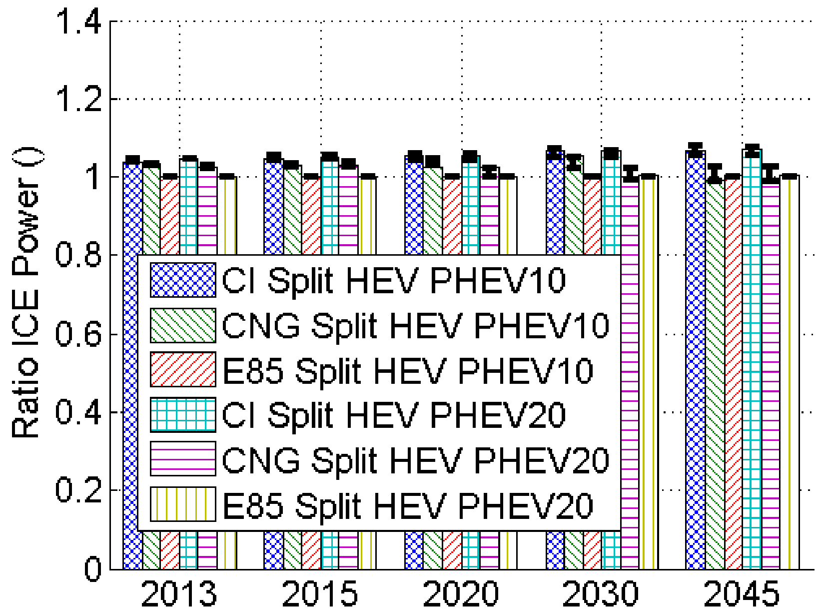


Figure 53 - ICE power for midsize PHEV10s and PHEV20s relative to gasoline PHEV with matching AER

ELECTRIC MACHINE

Figure 54 shows the peak power of the different electric machines for the PHEVs. The electric machines for the PHEV10 and PHEV20 cases were sized to have the capability to follow the UDDS drive cycle in EV mode. The electric machines for the PHEV30 and PHEV40 cases were sized to allow the vehicles to follow the US06 drive cycle. Technology evolution leads to power reductions ranging from 3% to 28% by 2045 for PHEV10s, from 3% to 28% for PHEV20s, from 5% to 28% for PHEV30s, and from 5% to 29% for PHEV40s (gasoline).

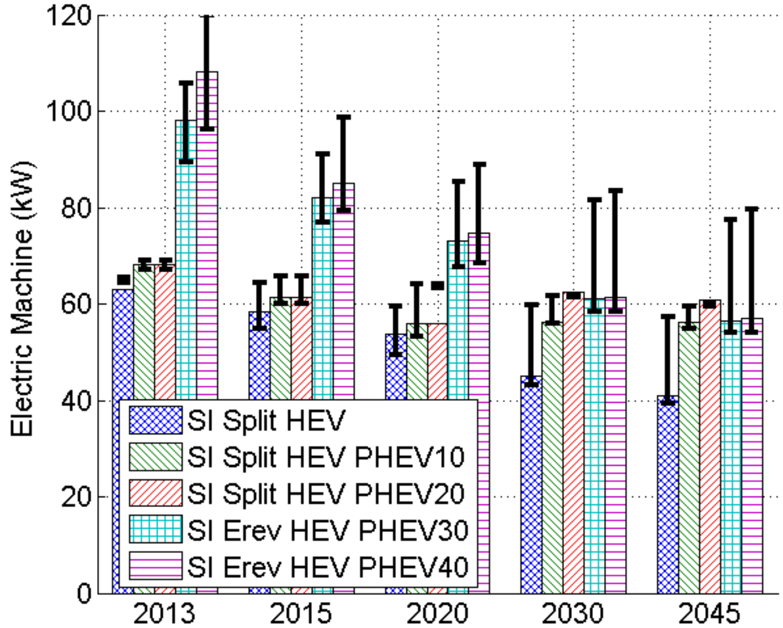


Figure 54 - Electric machine power for midsize PHEVs

BATTERY

Figure 55 shows that the battery power for the PHEV10 and PHEV20 decreases by 16% over time. The battery for the PHEV30 and PHV40 has nearly 3 times more power than for the PHEV10 and PHEV20, because of the need to follow the US06 cycle in electric-only mode. From one AER to the next, the battery power increases by an average of 2% for power-split and by an average of 3% for EREV powertrains.

Figure 56 shows that the usable battery energy is proportional to the AER for the various PHEVs. If the AER is multiplied by 2, the usable battery energy will also be multiplied by 2. For all of the AERs, the usable-energy decrease ranged from 4% to 30% by 2045.

The PHEVs all show a linear relationship between the usable battery energy and the vehicle mass (Figure 57). However, it appears that the higher the AER, the greater the slope.

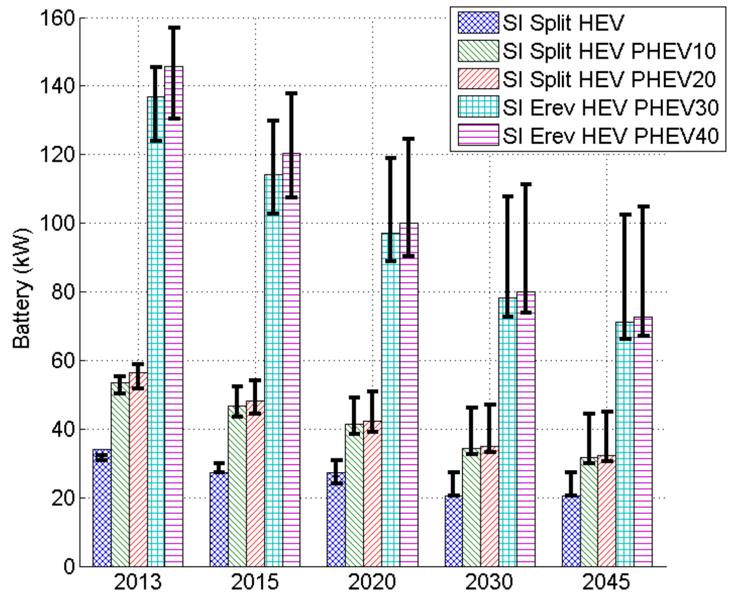


Figure 55 - Battery power for midsize gasoline HEV and PHEVs

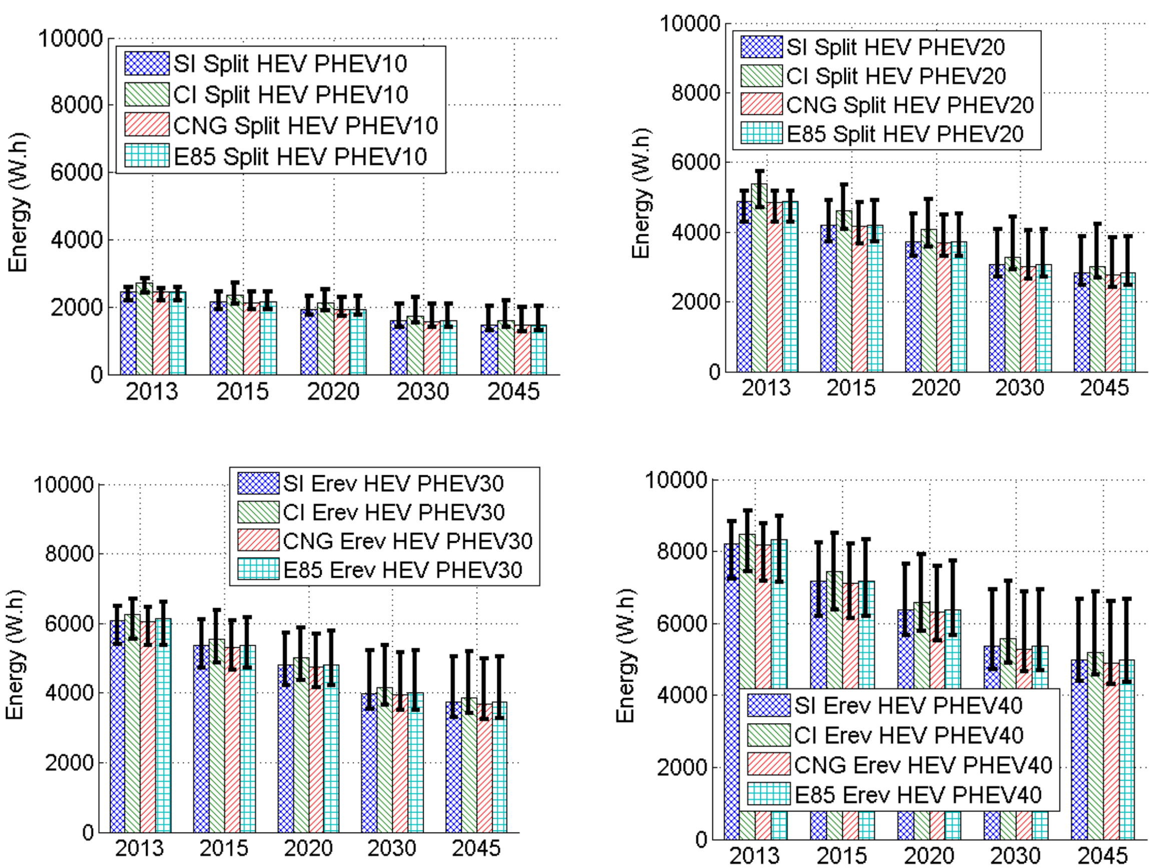


Figure 56 - Usable battery energy for midsize PHEV10, PHEV20, PHEV30, and PHEV40

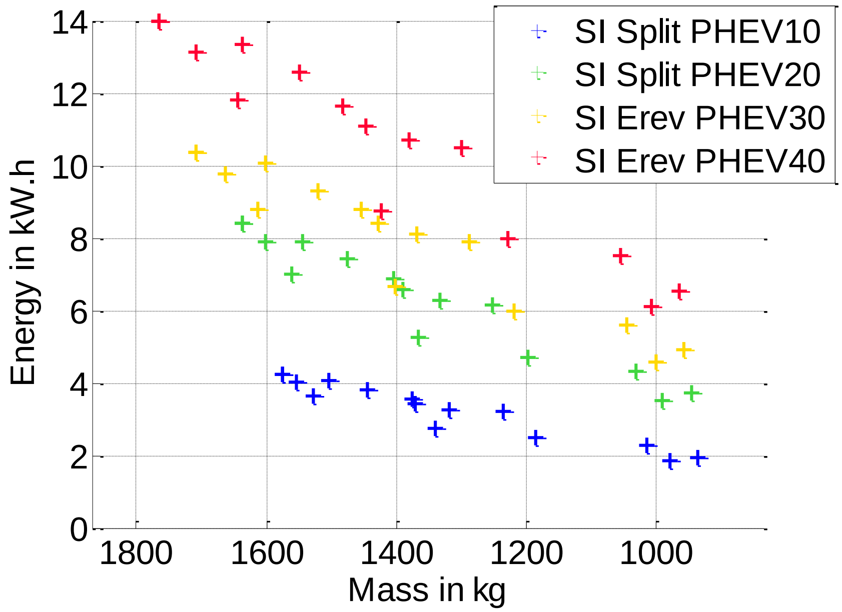


Figure 57 - Total battery energy as a function of vehicle mass for gasoline PHEVs

6.3.4. FUEL-CELL HEV

Fuel-cell systems, like other components, show a decrease in peak power over time (Figure 58), which is mostly due to vehicle lightweighting and better fuel efficiency. The total decrease from the reference case to the 2045 case ranged from 24% to 55%.

Figure 59 shows that the electric-machine peak power shows a decrease ranging from 17 to 42% between 2013 and 2045.

Total battery energy (Figure 60) shows a continuous decrease over time as well.

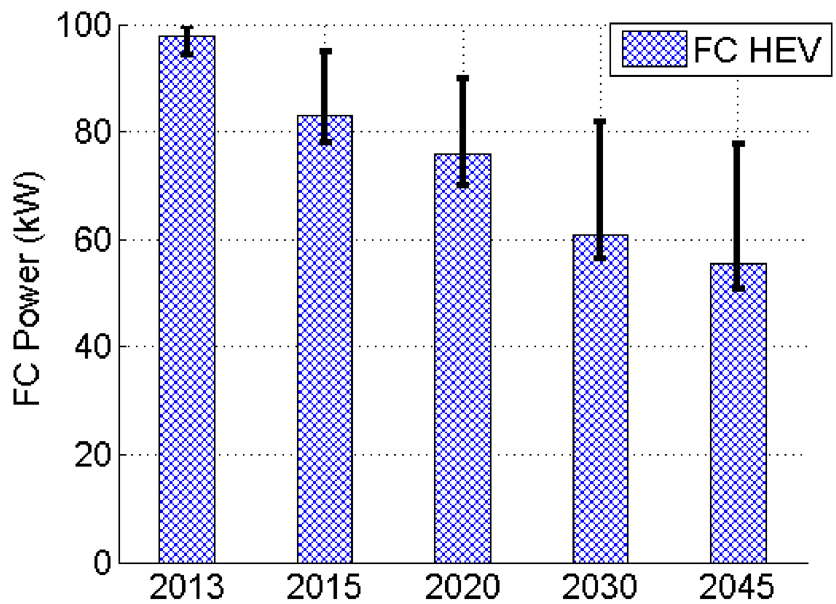


Figure 58 - Fuel-cell system power for midsize fuel-cell HEVs

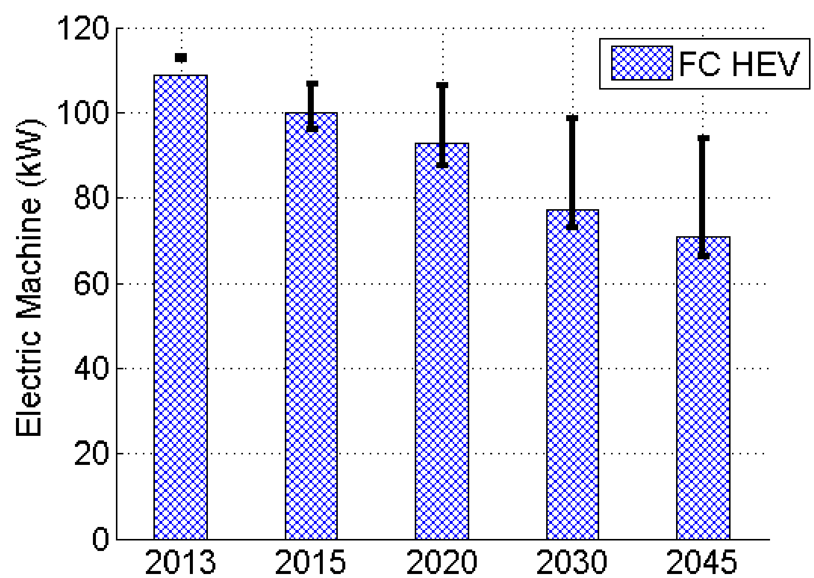


Figure 59 - Electric-machine power for midsize fuel-cell HEVs

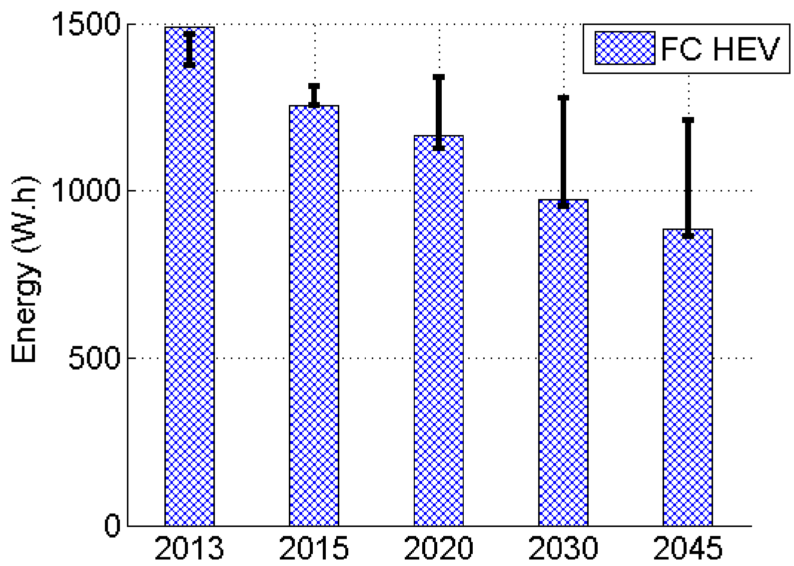


Figure 60 - Total battery energy for midsize fuel-cell HEVs

6.3.5. FUEL-CELL PHEV

The fuel-cell system power decreases over time for all the AERs, with a reduction that ranges from 19% to 45% (Figure 61). From one AER to another, the changes in fuel-cell power are very small.

As shown in Figure 62, in terms of usable battery energy, the same pattern described for power-split PHEVs can be observed for fuel-cell PHEVs. The energy is proportional to the AER and the energy decreases continuously over time. For all of the AERs, the usable battery energy is from 15% to 45% lower by 2045 compared with the reference case.

The electric-machine power continuously decreases by between 12% and 40% over time from the reference case to 2045 (Figure 63). The higher the AER, the higher the electric-machine power within the same year and case.

As shown in Figure 64, the battery energy has a linear relationship to vehicle mass, with a slope that increases with the AER.

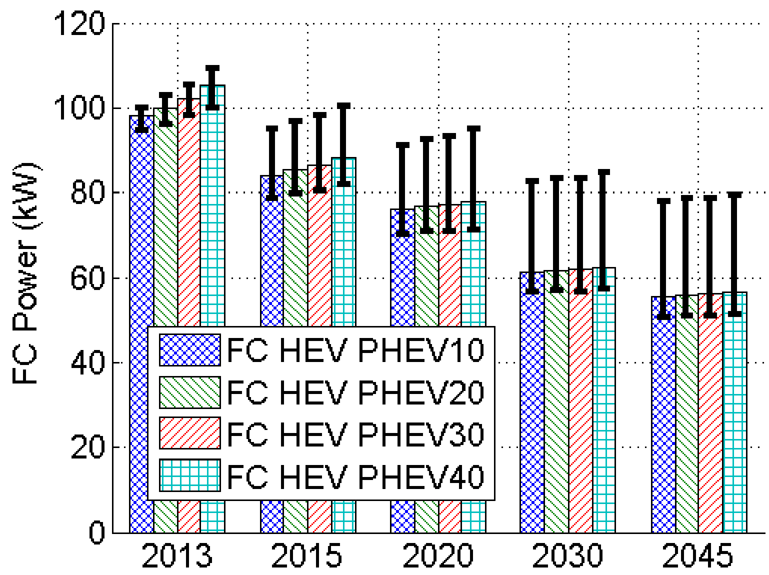


Figure 61 - Fuel-cell system power for midsize fuel-cell PHEVs

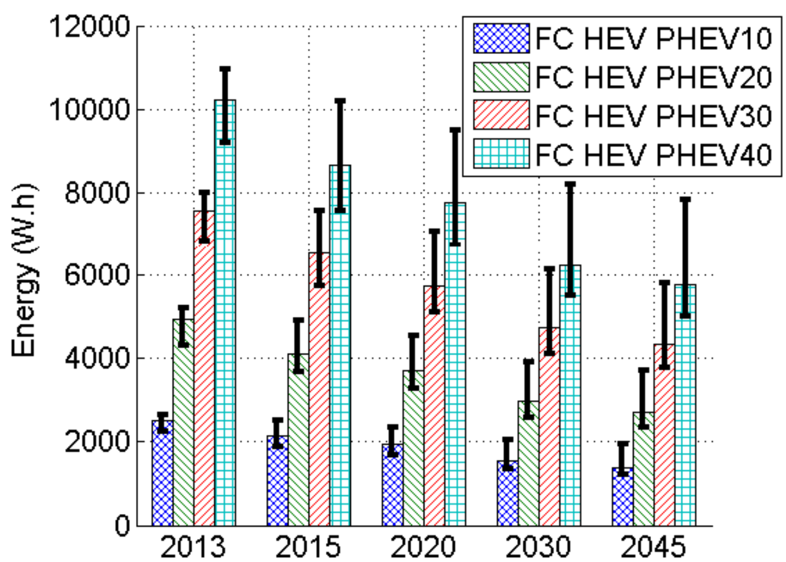


Figure 62 - Usable battery energy for midsize fuel-cell PHEVs

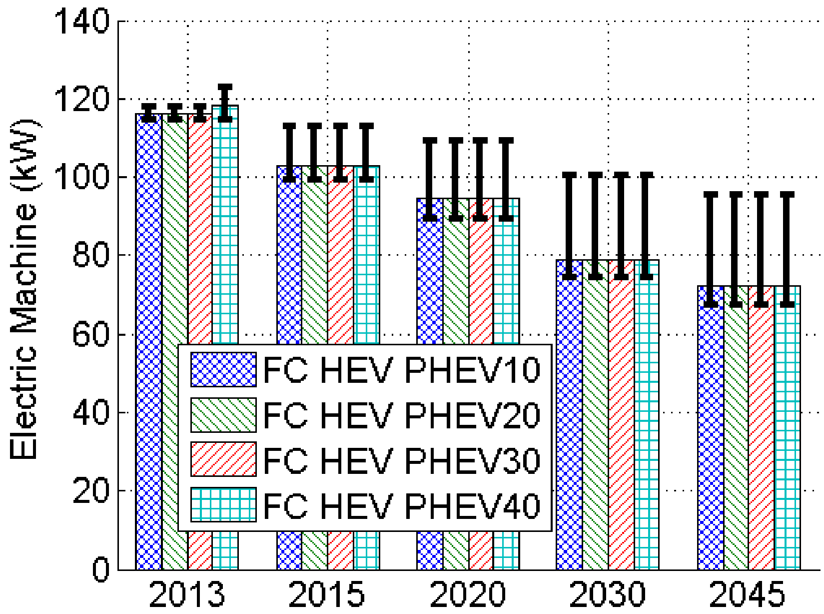


Figure 63 - Electric-machine power for midsize fuel-cell PHEVs

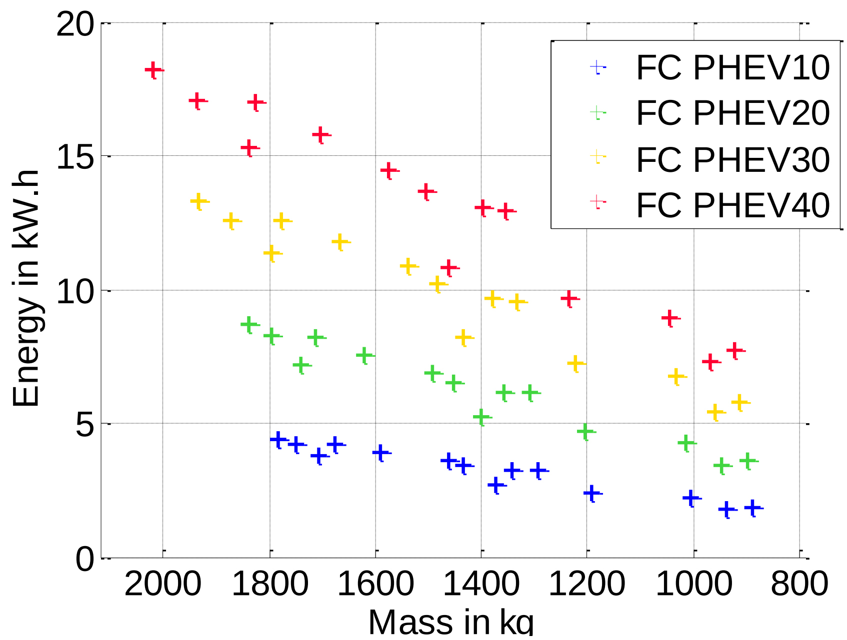


Figure 64 - Battery energy as a function of vehicle mass for midsize fuel-cell PHEVs

6.3.6. BATTERY ELECTRIC VEHICLE

Figures 65 and 66 show the impact of lightweighting and improved aerodynamics and tires on the electric-machine peak power for BEVs. The electric machine and the battery are more than 50% less powerful by 2045 compared with the reference case.

The decrease in usable energy for BEVs between the reference case and 2045 is cut in more than half as well (Figure 67).

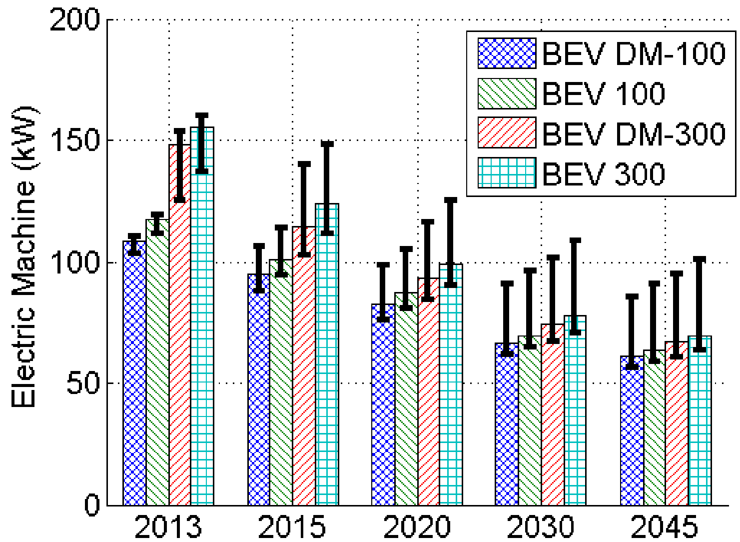


Figure 65 - Electric-machine power for midsize BEVs

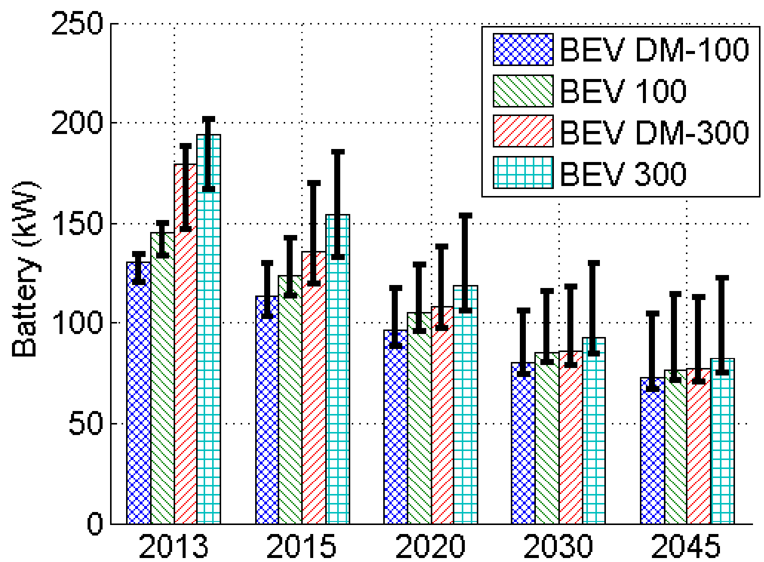


Figure 66 - Battery power for midsize BEVs

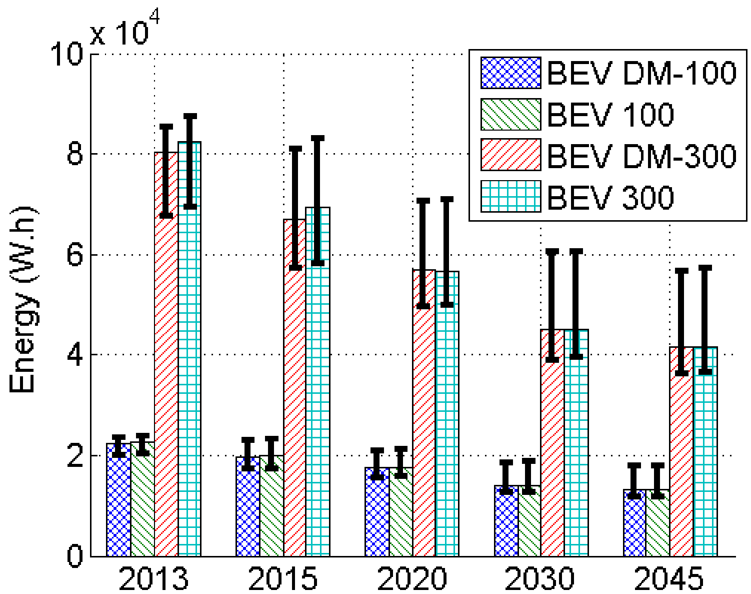


Figure 67 - Usable battery energy for midsize BEVs

7. TEST PROCEDURE AND CONSUMPTION CALCULATIONS

All the simulations were performed under hot conditions. The cold-start penalties were assessed after the simulations, on the basis of test data collected at Argonne's APRF and a literature search. A two-cycle test procedure, based on the UDDS and HWFET drive cycles, was used.

7.1. CONVENTIONAL VEHICLES

The conventional vehicle test procedure follows the current EPA two-cycle test procedure (EPA n.d.).

The urban cycle for a non-hybrid vehicle (Figure 68) is composed of four parts:

1. Bag 1: cold start
2. Bag 2: stop and go
3. Idling
4. Bag 3: hot start

The highway cycle for a non-hybrid vehicle is composed of only one part, the HWFET (Figure 69).

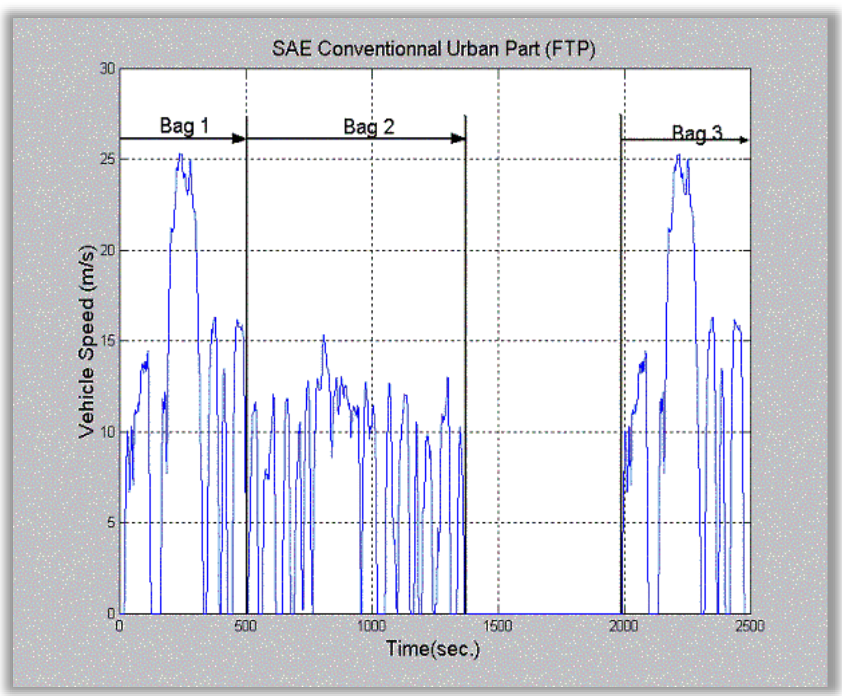


Figure 68 - The urban cycle for a non-hybrid vehicle

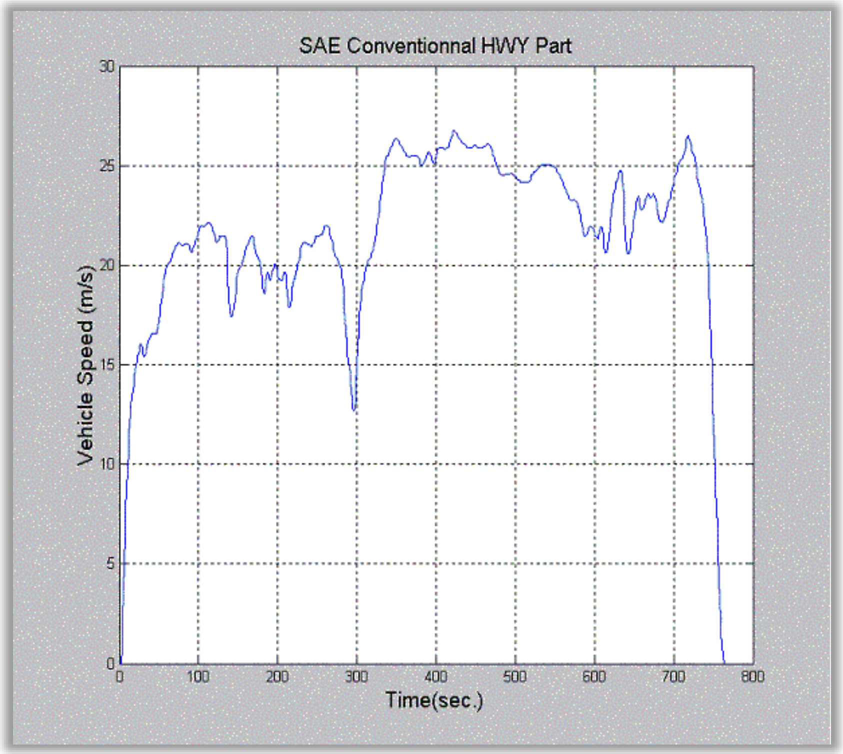


Figure 69 - The highway cycle for a non-hybrid vehicle

7.2. HYBRID ELECTRIC VEHICLES

The HEV procedure is similar to the conventional-vehicle procedure except that the drive cycles are repeated until the initial and final battery SOCs are within a tolerance of 0.5% (see Figures 70 and 71.)

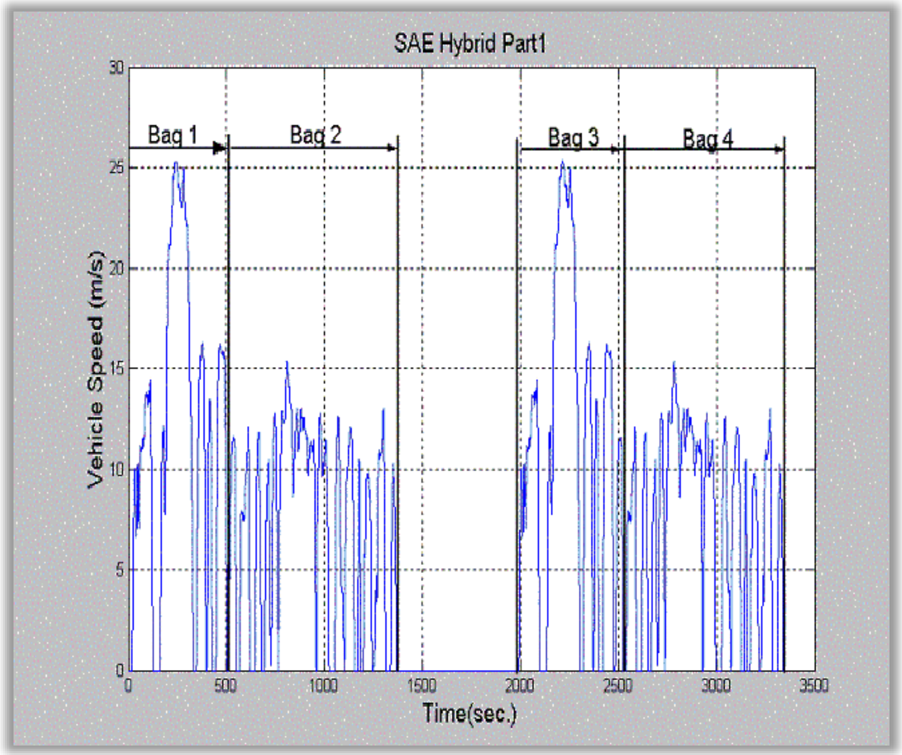


Figure 70 - The urban cycle for a hybrid vehicle

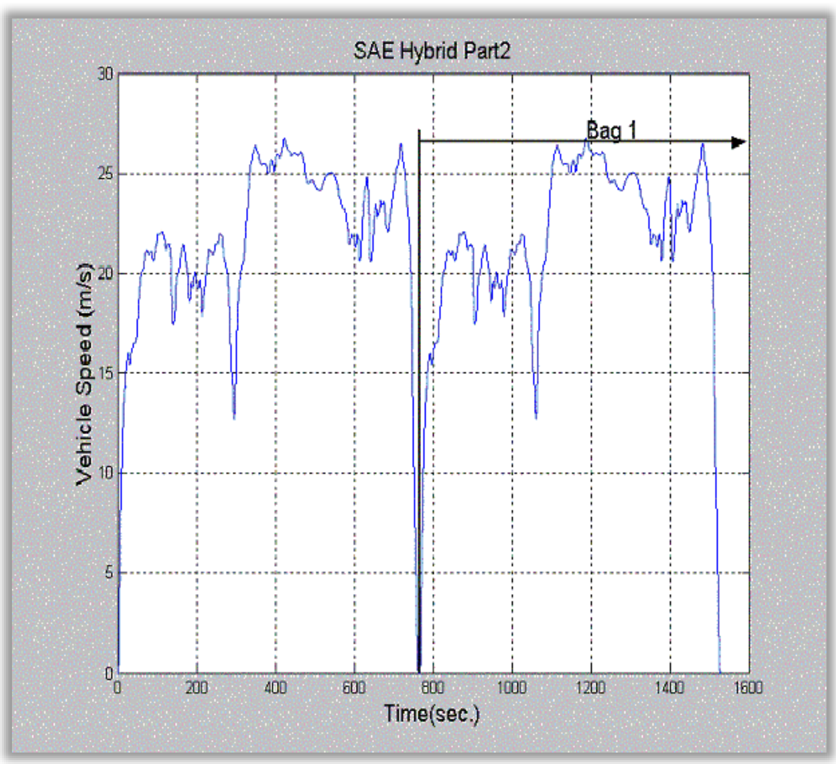


Figure 71 - The highway cycle for a hybrid vehicle (Only the results from the second cycle were used.)

7.2.1. TWO-CYCLE PROCEDURE CALCULATIONS FOR CONVENTIONAL AND HYBRID VEHICLES

FUEL CONSUMPTION

For the urban procedure, the fuel consumption was computed via Equation (1):

$$(1) \quad FC = 0.43\,\frac{V_{Fuel}^{1} + V_{Fuel}^{2}}{Dist_1 + Dist_2} + 0.57\,\frac{V_{Fuel}^{3} + V_{Fuel}^{Z}}{Dist_3 + Dist_Z}$$

Where

- V_{Fuel}^{y} = volume of fuel from Bag y,
- $Dist_y$ = distance driven by the vehicle for the Bag y part of the cycle, and
- Z = Bag 2 for a non-hybrid vehicle and Bag 4 for a hybrid.

The same equation was used to compute the gas-equivalent fuel consumption as well as the SOC-adjusted fuel consumption by replacing V_{Fuel} with the corresponding physical quantity.

The highway procedure results were the same as for a simple cycle, except for the hybrid case, where only the results from Bag 1 were used to compute the values:

$$(2) \quad FC = \frac{V_{Fuel}^{2}}{Dist}$$

COMBINED FUEL CONSUMPTION

The combined fuel consumption is a weighted value lying between the urban and highway cycles:

$$(3) \quad FC^{combined} = 0.55 \times FC^{urban} + 0.45 \times FC^{highway}$$

7.3. PLUG-IN HYBRID ELECTRIC VEHICLES

This section describes the methodology currently implemented in Autonomie to support the Government Performance and Results Act (GPRA). The implementation is based on the J1711 procedure. The procedure is divided into several phases, as described below.

7.3.1. CHARGE-SUSTAINING ON THE UDDS CYCLE

1. Set battery SOC to charge-sustaining (CS) value.
2. Run UDDS.
3. 10-minute soak with the key off.

4. Run UDDS.
5. Assume the cycle charge is balanced. Display warning if it does not meet 1%.

Weightings and cold factor correction:

The following equations demonstrate the cold compensation:

$$(4) \quad M^*_{0-505} = \frac{M_{0-505}}{1 - CF_{75F}}$$

Where

M_{0-505} = fuel mass consumed during the time window between 0 and 505 sec,

CF_{75F} = cold-factor correction at 75°F, and

M^*_{0-505} = cold-corrected mass of fuel.

$$(5) \quad Vol^*_{0-505} = \frac{M^*_{0-505}}{\delta_{gasoline}}$$

Where

Vol^*_{0-505} = volume of fuel consumed during the time window between 0 and 505 sec, and

$\delta_{gasoline}$ = density of gasoline.

One can then calculate FC^{UDDS}, the fuel consumed on the UDDS cycle:

$$(6) \quad FC^{UDDS} = 0.43 \times \left(\frac{Vol^*_{0-505} + Vol_{506-1372}}{D_{0-505} + D_{506-1372}}\right) + 0.57 \times \left(\frac{Vol_{1972-2477} + Vol_{2478-3340}}{D_{1972-2477} + D_{2478-3340}}\right)$$

7.3.2. CHARGE-SUSTAINING ON THE HWFET CYCLE

1. Set battery SOC to CS value.
2. Run HWFET.
3. Wait 4 sec.
4. Run HWFET.
5. Assume the cycle is charge balanced.
6. Perform calculations on the second HWFET cycle.

$$(7) \quad FC^{HWFET} = \frac{Vol_{765-1529}}{D_{765-1529}}$$

Where

$Vol_{765-1529}$ = volume of fuel consumed during the time window between 765 and 1,529 sec,

$D_{765-1529}$ = distance traveled during the time window between 765 and 1,529 sec, and

FC^{HWFET} = highway fuel consumption.

7.3.3. CHARGE-DEPLETING ON THE UDDS AND HWFET CYCLES

1. The calculations are identical for the UDDS and HWFET cycles.
2. Set battery SOC to full charge test initial SOC.
3. Run UDDS (HWFET).
4. 10-minute soak with the key off (15-sec pause with key on).
5. Run UDDS (HWFET).
6. 10-minute soak with the key off (15-sec pause with key on).
7. Repeat until SOC reaches the CD/CS crossover point and the last cycle is completed.
8. Round down the number of cycles unless the CD range is less than one cycle. In that case, round up the number of cycles. At least 1 CD cycle is required to run the analysis.

Cold weighting calculation:

The user specifies the number of cycles over which to apply the cold correction factor:

$$(8) \quad N_{cold} = \min(\mathrm{N}_{\mathrm{cold}}^{\mathrm{user}}, \mathrm{N}_{\mathrm{cd}})$$

$$(9) \quad N_{hot} = N_{cd} - N_{cold}$$

Where

N_{cold} = number of cold cycles,

N_{hot} = number of hot cycles,

$\mathrm{N}_{\mathrm{cold}}^{\mathrm{user}}$ = number of user-specified cold cycles, and

N_{cd} = total number of CD cycles.

$$(10) \quad M_{cd} = \left[\frac{\alpha_{cold} M_{cd-cold}^{1}}{1 - CF_{75F}}, \cdots, \frac{\alpha_{cold} M_{cd-cold}^{N_{cold}}}{1 - CF_{75F}}, \alpha_{hot} M_{cd-hot}^{1}, \cdots, \alpha_{hot} \mathrm{M}_{cd-hot}^{N_{hot}}\right]^{T}$$

Where

$M_{cd-cold}^{1}$ = mass of fuel consumed during the first cold CD cycle,

$M_{cd-cold}^{N_{cold}}$ = mass of fuel consumed during the last cold CD cycle,

CF_{75F} = cold-start fuel economy penalty at 75°F,

M_{cd-hot}^{1} = mass of fuel consumed during the first hot CD cycle,

$\mathrm{M}_{cd-hot}^{N_{hot}}$ = mass of fuel consumed during the last hot CD cycle,

α_{cold} = user-specified cold weighting factor (default value = 0.43),

α_{hot} = user-specified hot weighting factor (default value = 0.57), and

M_{cd} = column vector of cold-corrected fuel mass.

$$(11) \quad Vol_{cd} = \frac{M_{cd}}{\delta_{gasoline}}$$

Where

Vol_{cd} = column vector of cold-corrected fuel volumes.

Note that each element in the Vol_{cd} vector is divided by its respective distance:

$$(12) \quad FC_{cd} = \frac{Vol_{cd}}{D_{udds}}$$

Where

FC_{cd} = column vector of cold-corrected fuel consumptions.

The net battery energy used was calculated for each cycle using the open-circuit voltage and the current.

$$(13) \quad for\ i = 1, \cdots, N_{cd}\ ;\ E_{cd}^{i} = \int_{(i-1)T_{udds}}^{(i)T_{udds}+t} V_{oc}(\tau) * I(\tau) d\tau$$

Where

E_{cd}^{i} = net battery energy used during the i^{th} CD cycle,

T_{udds} = duration of the UDDS cycle + soak time or (HWFET + 15 sec),

i = index of the CD cycle,

N_{cd} = total number of CD cycles,

V_{oc} = open-circuit voltage as a function of time during the cycle, and

I = battery current as a function of time during the cycle.

$$(14) \quad E_{cd} = \left[E_{cd}^{1}, \cdots, E_{cd}^{N_{cd}}\right]^{T}$$

Where

E_{cd} = column vector of net battery energy used on each cycle.

Note that each element in the E_{cd} vector is divided by its respective distance.

$$(15) \quad EC_{cd} = \frac{E_{cd}}{D_{udds} * \eta_{chg}^{ess} * \eta_{charger}}$$

Where

EC_{cd} = column vector of electrical-energy consumption in AC-Joules (wall outlet),

D_{udds} = distance traveled on a UDDS (or $HWFET - D_{HWFET}$) cycle,

η_{chg}^{ess} = user-definable efficiency of the battery during charging (default value = 0.99), and

$\eta_{charger}$ = user-definable efficiency of the charger (wall or in-vehicle) (default value = 0.94).

$$(16) \quad for\ i = 1, \cdots, N_{cd}\ ;\ \mu_i = \mu\left(i * D_{udds}^{i}\right) - \mu(i-1) * D_{udds}^{i}$$

$\mu_{cd} = \left[\mu_1, \cdots, \mu_{N_{cd}}\right]$

Where

μ_{cd} = row vector of utility factors,

μ_1 = utility factor on the first CD cycle,

μ_i = utility factor on the i^{th} CD cycle,

$\mu_{N_{cd}}$ = utility factor on the last CD cycle, and

μ = fleet Mileage Fraction Utility Factor as a function of distance.

$$(17) \quad FC = \mu_{cd} FC_{cd} + \left(1 - \sum_{i}^{N_{cd}} \mu_i\right) FC_{cs}$$

Where

FC= fuel consumed on the city or highway portion of the PHEV procedure.

$$(18) \quad EC = \mu_{cd} EC_{cd}$$

Where

EC = electrical energy consumed during the city or highway portion of the PHEV procedure.

Consumption adjustment factors:

Although *only unadjusted values were used to support NEMS (National Energy Modeling System), MARKAL, and SEDS (State Energy Data System)*, this section describes the adjusted fuel-consumption values provided.

$$(19) \quad FE_{adj}^{udds} = 0.003259 + 1.1805 * FE^{udds}$$

$$(20) \quad FE_{adj}^{hwfet} = 0.001376 + 1.3466 * FE^{hwfet}$$

$$(21) \quad FC_{adj}^{combined} = 0.55 * FC_{adj}^{udds} + 0.45 * FC_{adj}^{hwfet}$$

Electrical consumption (corrected) = 0.7 * electrical consumption, per communication with EPA.

7.4. ELECTRIC VEHICLES

Start the battery at full SOC and run until minimum SOC is reached:

$$C = \frac{\int V_{oc} * I_{ess}}{\eta_{ess}\eta_{charger}} \quad (22)$$

Where

η_{ess} = efficiency of the battery while charging,

$\eta_{charger}$ = average efficiency of the charger while charging,

V_{oc} = open-circuit voltage as a function of time over the cycle, and

I_{ess} = current as a function of time over the cycle.

7.5. COLD-START PENALTY

A cold-start penalty of 20% is applied over four UDDS cycles for the CD results.

Table 9 summarizes the cold-start penalties applied to the UDDS CS results for the different powertrains.

Table 9: Cold-start (20°C) penalties for the different powertrain configurations (%)

	2013-2045		
Powertrain	**Low**	**Med**	**High**
Conventional	12	10	6
Power-Split HEV	12	10	6
Power-Split PHEV	12	10	6
Fuel Cell HEV	12	10	6
Fuel Cell PHEV	0	0	0
Electric	0	0	0

8. SIMULATION RESULTS

All the fuel-consumption results shown in this report are expressed in liters (L) per 100 km. The reasons behind this decision came from the analysis of the data shown in Figure 72, which shows the relationship between fuel economy (expressed in mi per gal) and fuel consumption (expressed in gal per 1,000 mi). There is no linear relationship between fuel consumption and fuel economy. For example, if you improve your fuel economy from 15 to 30 mpg, you will save approximately 37 gal of fuel per 1,000 mi; whereas if you improve your fuel economy from 50 to 100 mpg, you will save only 10 gal per 1,000 mi. By comparing two different values of fuel consumption, one immediately knows the amount of fuel saved and thus the amounts of money and emissions saved, since they are linearly linked to the fuel consumption.

Moreover, whereas different vehicles can drive miles at a different pace, they all have roughly the same lifetime mileage.

Unless otherwise specified, all the fuel-consumption results are provided for the combined drive cycle using unadjusted values based on gasoline equivalent.

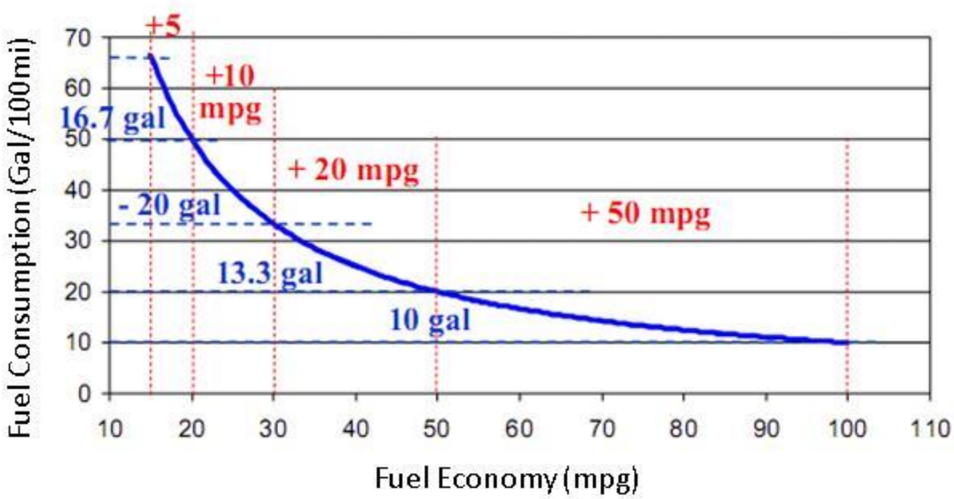


Figure 72 - Fuel economy versus fuel consumption

8.1. EVOLUTION OF SPECIFIC POWERTRAIN CONFIGURATIONS

8.1.1. CONVENTIONAL POWERTRAIN

Figure 73 shows that fuel consumption decreases over time across fuels. Gasoline conventional midsize vehicles consume from 40% to 65% less fuel by 2045 compared with the reference case; the change is different for diesel vehicles, with a reduction in fuel consumption ranging from 36% to 54%. CNG vehicles will achieve the highest improvements in fuel consumption between the reference case and 2045, with a decrease ranging from 14% to 34%, whereas ethanol shows the widest range of improvement, with a decrease ranging from 30% to 56%.

The ethanol-engine and gasoline vehicles have the highest fuel consumption among conventional vehicles for all timeframes (except for the reference case). Figure 74 shows the fuel consumption relative to the reference gasoline conventional vehicle. In 2045, compared with the gasoline reference case, the ranges of improvement were as follows: gasoline engine, 40% to 65%; diesel-engine, 43% to 63%; CNG engine, 21% to 43%; and ethanol engine, 30% to 60%.

Figure 75 shows the fuel consumption relative to that of the conventional gasoline vehicle of the same year. Notice that the differences between gasoline and diesel will tend to decrease in the future. In some cases (i.e., 2045 high case), both fuels achieve similar gasoline-equivalent fuel consumption. Overall, even if the fuel consumption of the CNG and ethanol engine improve in the future (Figure 74), they will still remain less efficient than any other fuel on a volumetric basis.

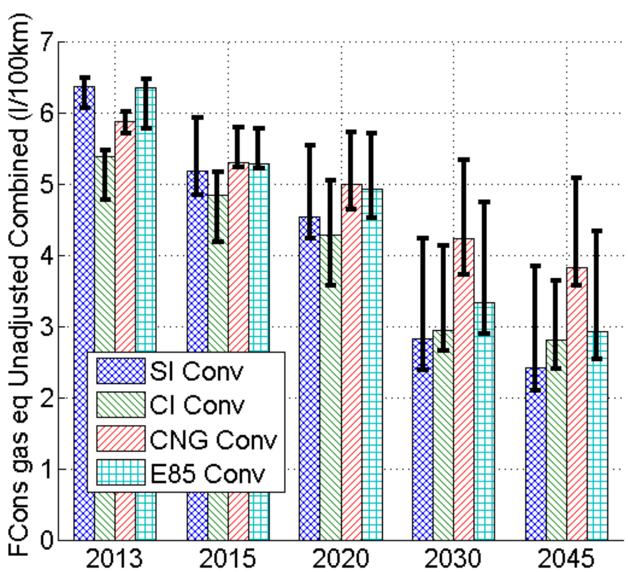


Figure 73 - Fuel consumption (gasoline equivalent) for conventional midsize cars

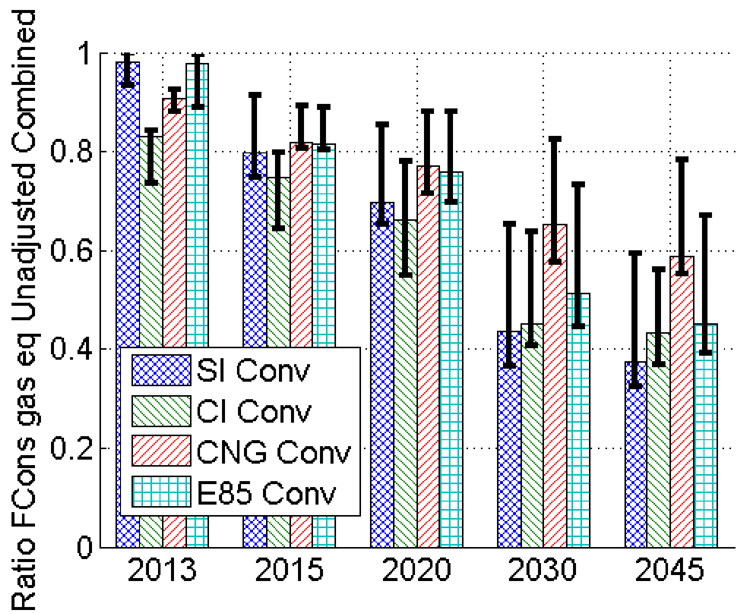


Figure 74 - Gasoline-equivalent fuel consumption for conventional midsize cars, compared with the reference conventional gasoline vehicle

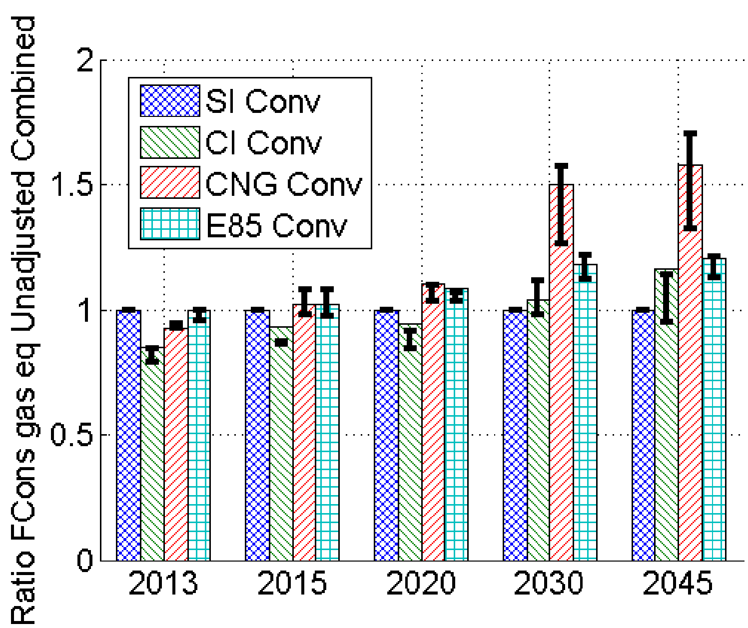


Figure 75 - Gasoline-equivalent fuel consumption for conventional midsize cars, compared with the same-year conventional gasoline vehicle

8.1.2. HEV ENGINE

Figure 76 shows that fuel consumption for HEVs is expected to decrease significantly over time.

Figure 77 shows the fuel consumption compared with the HEV reference gasoline vehicle. The ratio between CNG and gasoline reaches 0.55 in the 2045 high-uncertainty case, which shows the dramatic improvements that can be expected from CNG power-split vehicles.

Figure 78 shows the fuel-consumption ratios for HEVs with various fuels compared with the HEV gasoline vehicle of the same year. The results show that the ethanol fuel will maintain a fuel consumption between 5% and 18% higher than the gasoline case, and it will have the highest fuel consumption over all the timeframes. The diesel power-split vehicles will have about 7% lower fuel consumption than the gasoline vehicles across all timeframes.

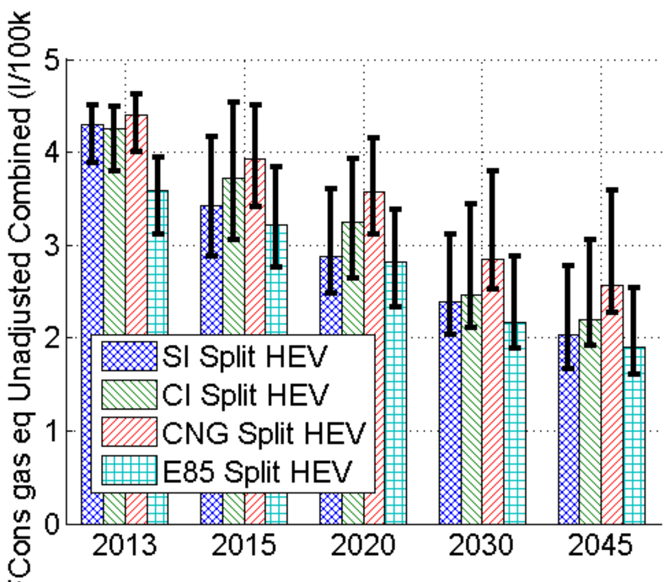


Figure 76 - Gasoline-equivalent fuel consumption for midsize split HEVs

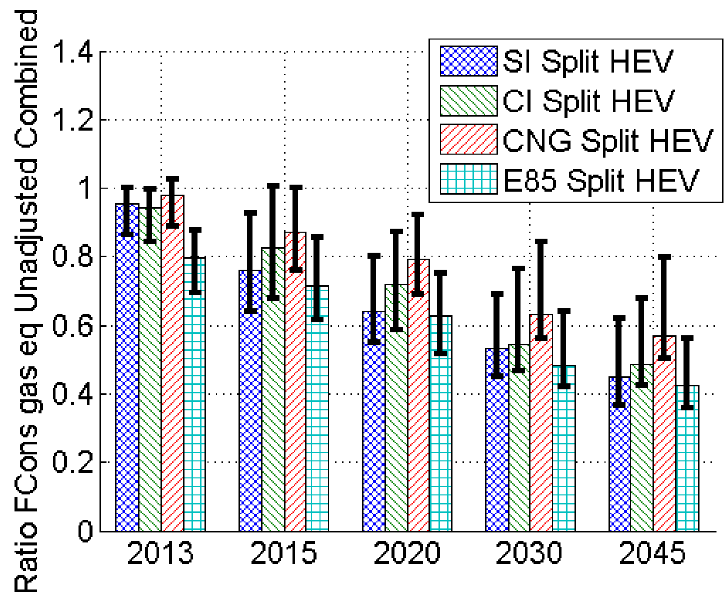


Figure 77 - Gasoline-equivalent fuel consumption of midsize split HEVs, compared with the reference gasoline split-HEV

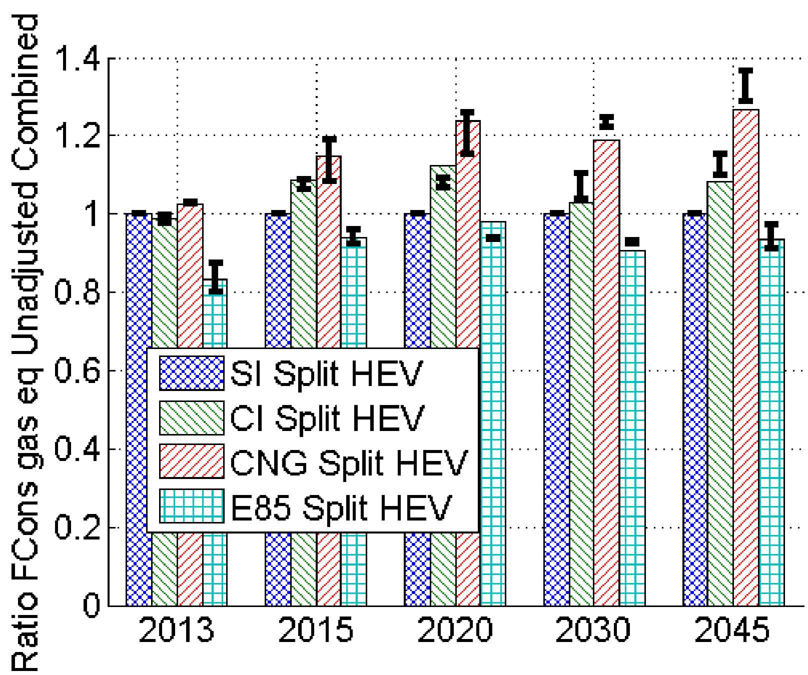


Figure 78 - Gasoline-equivalent fuel consumption for split-HEV midsize cars, compared with the same-year, same-case gasoline HEV

8.1.3. PHEV ENGINE

The fuel-consumption evolution for power-split PHEVs is similar to that for power-split HEVs. The CNG vehicles always have the highest fuel consumption (~7% more than the gasoline vehicles).

For the same fuel, the fuel consumption decreases slowly with the AER. The bigger the battery, the less fuel is consumed. However, there is no clear relationship between battery size and specific fuel-consumption improvement. For instance, between the reference case and 2045, the fuel-consumption improvement of gasoline engines was about 42% for PHEV10, 44% for PHEV20, 30% for PHEV30, and 33% for PHEV40. These variations do not show a trend related to battery size and improvement over the years. Data for PHEV10s and PHEV20s are shown in Figure 79, and for PHEV30s and 40s in Figure 80.

Table 10 shows the PHEV10 fuel consumption for the reference and 2045 technologies; as in the HEV case, gasoline shows the most improvement of any fuel between 2013 and 2045. The results for HEVs and PHEVs are very close to each other, since the engines are used under similar conditions.

Figure 81 shows the fuel consumption for the PHEV10 and PHEV20 compared with the same-year PHEV gasoline vehicle.

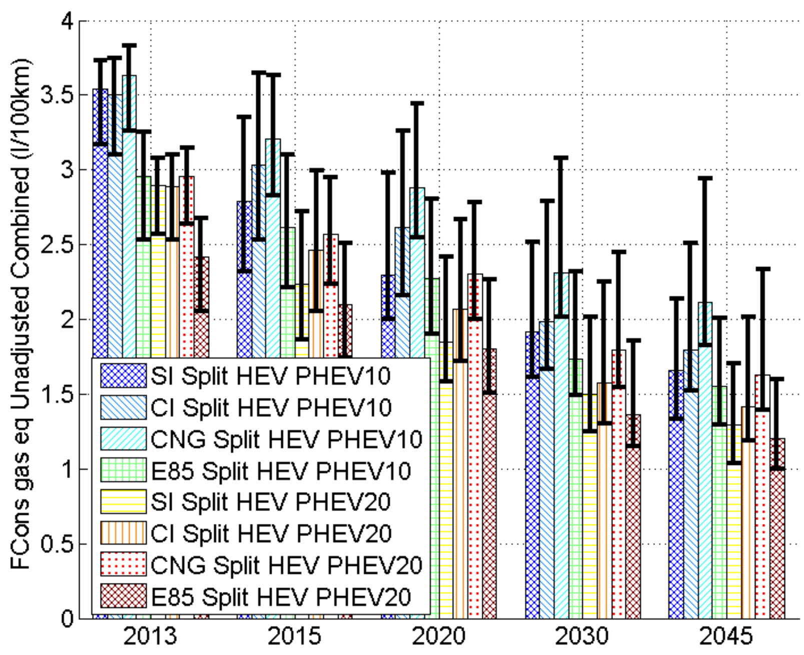


Figure 79 - Gasoline-equivalent fuel consumption for midsize split PHEV10s and PHEV20s (All the fuel-consumption values are CD+CS.)

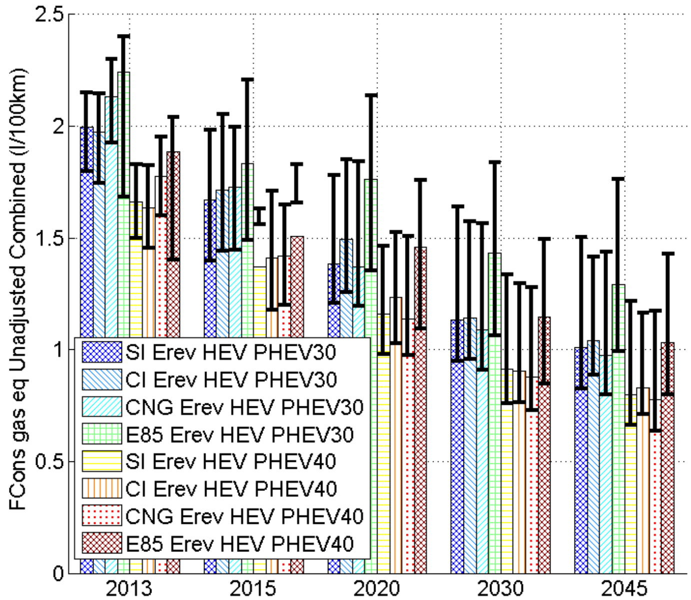


Figure 80 - Gasoline-equivalent fuel consumption for midsize split PHEV30s and PHEV40s (All the fuel-consumption values are CD+CS.)

Table 10: Fuel consumption of midsize PHEV10s with 2013 and 2045 technologies

	Power-Split PHEV10		
	Fuel Cons. (L/100 km)		
	Ref	**2045 low/med/high**	**Improvement**
SI	3.7	2.1/1.6/1.3	42%/55%/64%
CI	3.6	2.5/1.7/1.5	33%/52%/59%
CNG	3.8	2.9/2.1/1.8	23%/44%/52%
E85	3.2	2/1.5/1.2	38%/52%/60%

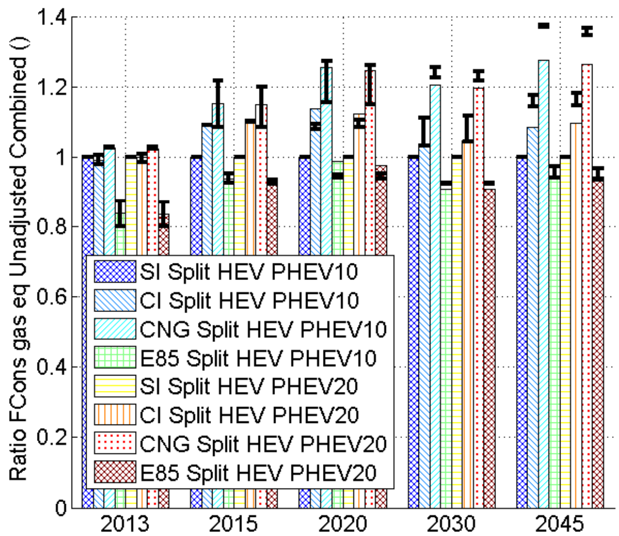


Figure 81 - Gasoline-equivalent fuel consumption for split PHEV10 and PHEV20 midsize cars, compared with the same-year, same-case gasoline PHEV with matching AER (All the fuel-consumption values are CD+CS.)

Figure 82 shows the fuel-consumption ratios for the PHEV10 and PHEV20 compared with the reference PHEV gasoline vehicle.

Figure 83 shows the fuel consumption for the PHEV30 and PHEV40 compared with the same-year PHEV gasoline vehicle. It is interesting to see that there is not really a linear trend for fuel-consumption ratios versus the same-year gasoline PHEV (Figure 84).

Figure 85 shows that there is a linear relationship between vehicle mass and electric consumption. The bigger the vehicle, the higher the electrical consumption. This observation is consistent with the fuel-consumption increase with vehicle mass. Because of the different energy density assumption used for split vehicles and EREVs, the figure shows a separation of the two configurations' electric consumption.

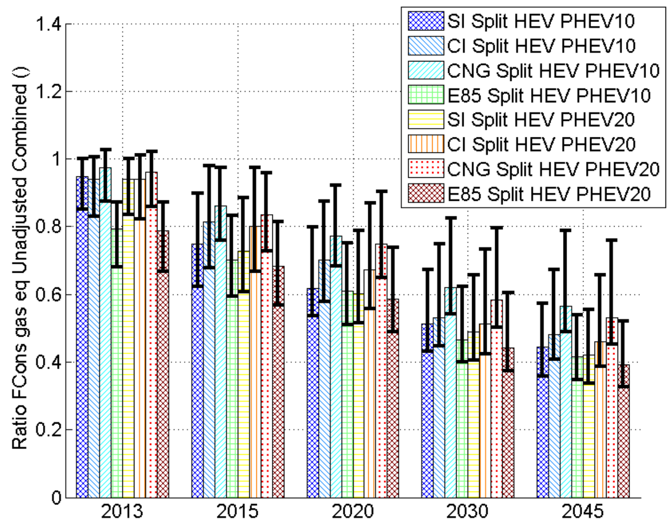


Figure 82 - Gasoline-equivalent fuel consumption for split PHEV10 and PHEV20 midsize cars, compared with the reference PHEV gasoline vehicle (All the fuel consumption values are CD+CS.)

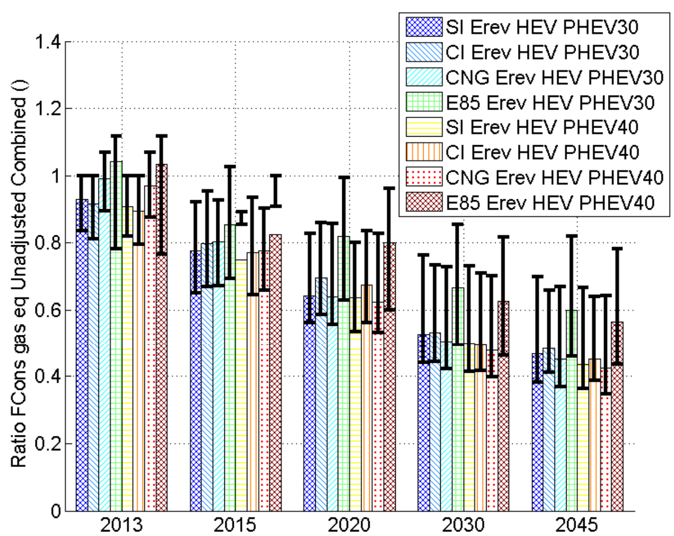


Figure 83 - Gasoline-equivalent fuel consumption for split PHEV30 and PHEV40 midsize cars, compared with the reference PHEV gasoline vehicle (All the fuel consumption values are CD+CS.)

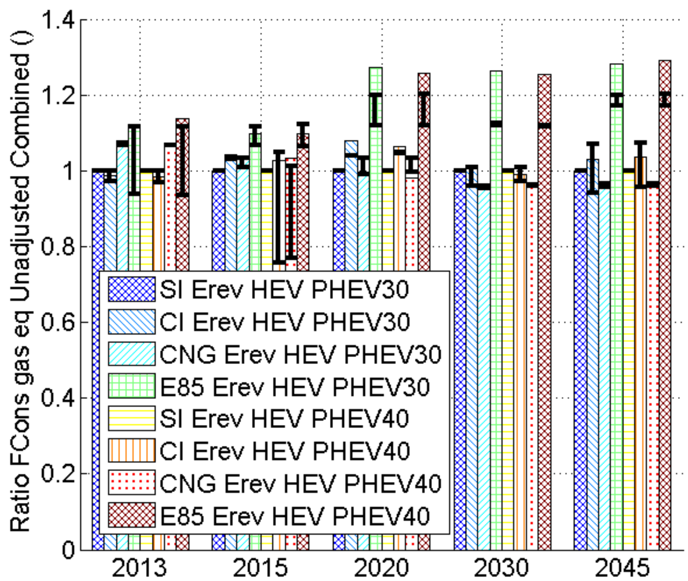


Figure 84 - Gasoline-equivalent fuel consumption for split PHEV30 and PHEV40 midsize cars, compared with the same-year, same-case gasoline PHEV with matching AER (All the fuel consumption values are CD+CS.)

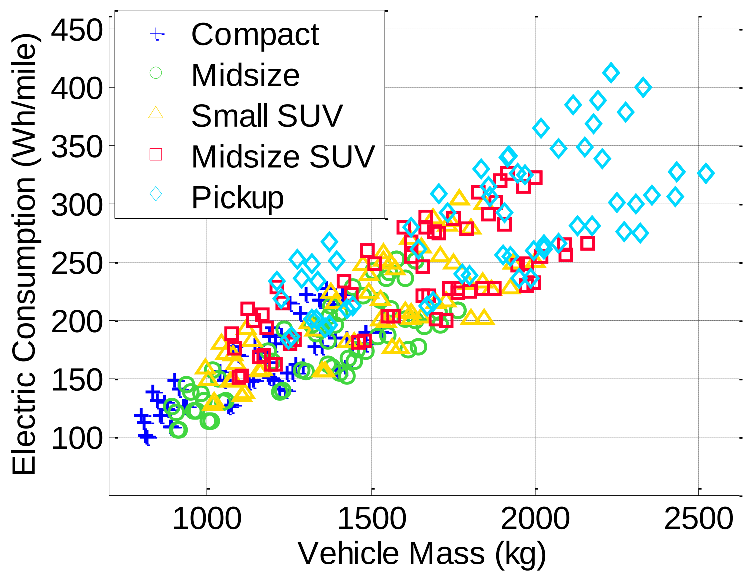


Figure 85 - Electric consumption in CD+CS mode for gasoline-powered-split PHEVs

8.1.4. FUEL-CELL HEV

The fuel-cell HEV's fuel consumption (Figures 86 and 87) decreases from 2013 to 2045. In 2045, the fuel consumption is from 19% to 50% lower than in the reference case.

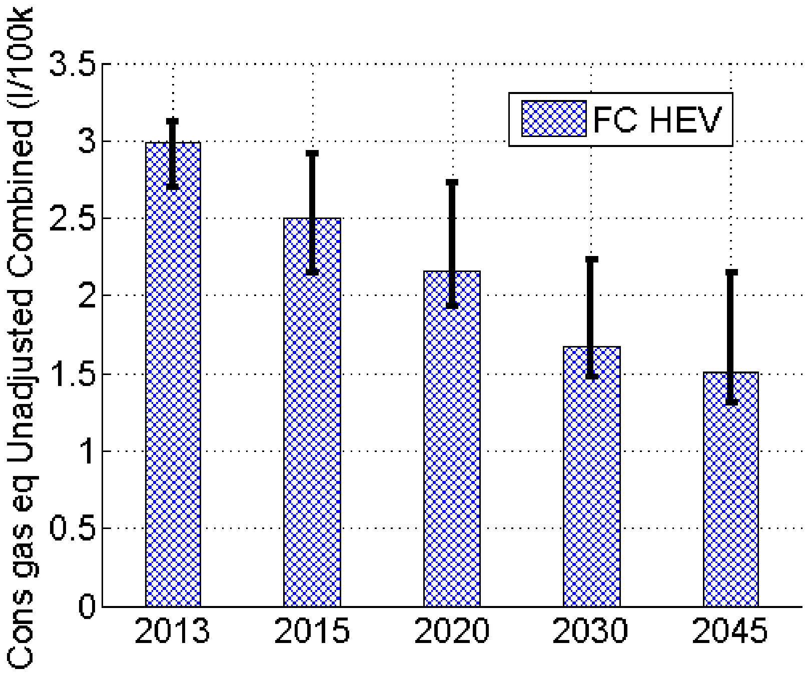


Figure 86 - Gasoline-equivalent fuel consumption for midsize fuel-cell HEVs

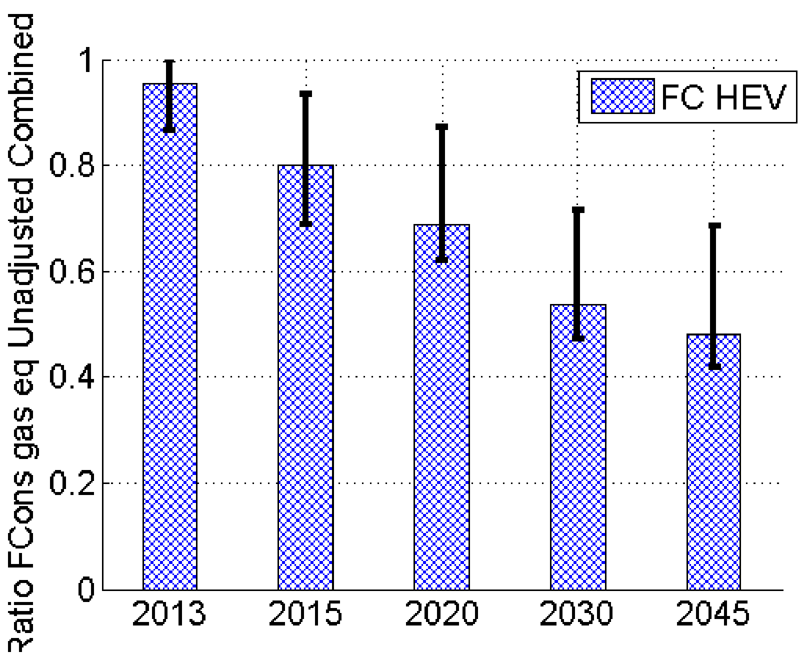


Figure 87 - Gasoline-equivalent fuel consumption compared with the midsize fuel cell HEV reference case

8.1.5. FUEL-CELL PHEV

For fuel-cell PHEVs, the fuel consumption decreases slowly (Figures 88 and 89) as the AER goes from one range to the next higher range, for the same reasons discussed for power-split PHEVs. From the reference case to 2045, the consumption decreases by 33% to 54% for all the AERs.

Figure 90 shows that electricity consumption also decreases slowly from 2013 to 2045, although initial consumption levels increase within AER for any given year.

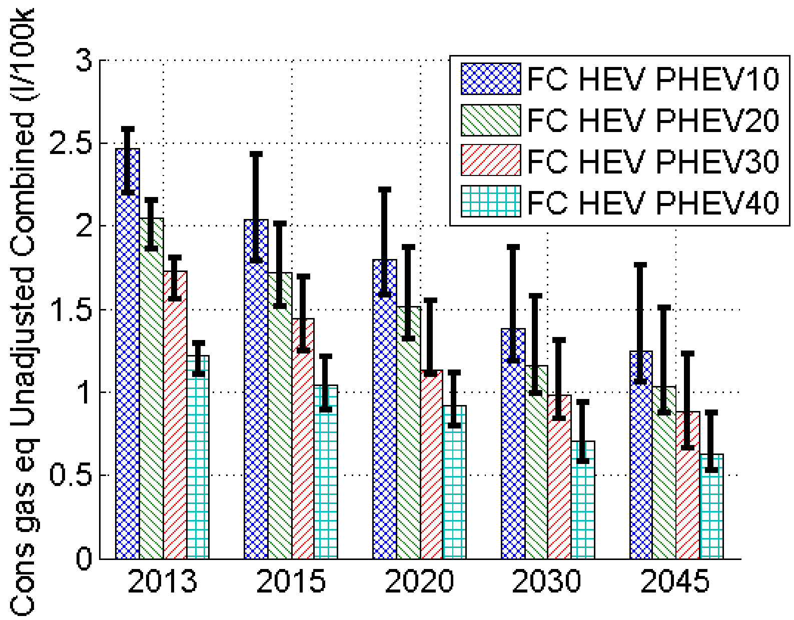


Figure 88 - Gasoline-equivalent fuel consumption for midsize fuel-cell PHEVs (The fuel consumption values are CD+CS.)

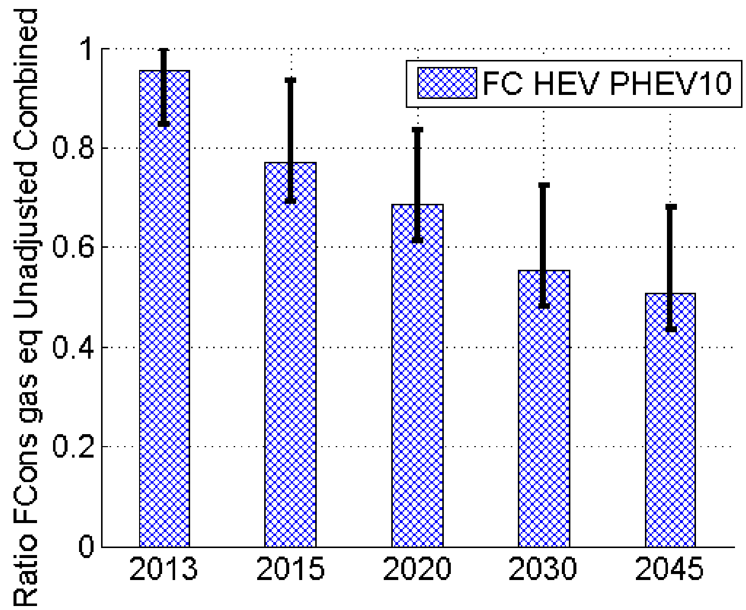


Figure 89 - Gasoline-equivalent fuel consumption for midsize fuel-cell PHEV10s compared with the reference case

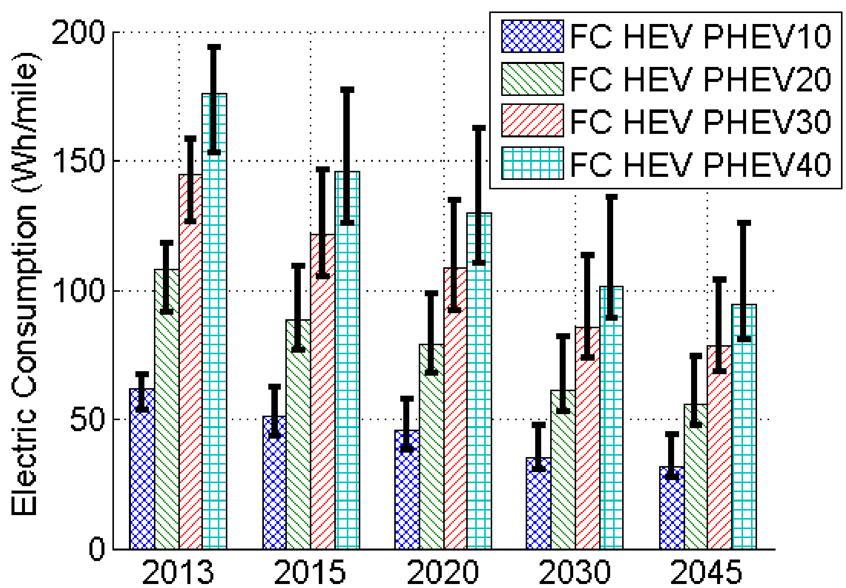


Figure 90 - Electric consumption in CD+CS mode for midsize fuel-cell PHEVs

8.1.6. ELECTRIC VEHICLES

For EVs, the results are given in terms of electric-energy consumption for the two drive cycles used in the simulations: UDDS and HWFET. The combination of lightweighting and component improvements leads to a significant decrease in electrical consumption over time.

The values expressed in Wh/mi represent the average energy provided by the battery to drive the vehicle for 1 mi. As shown in Figure 91, the HWFET electric consumption is consistently higher than for a UDDS cycle. This can be explained by looking at the two drive-cycle shapes and the energy recoverable by regenerative braking. The UDDS cycle has many strong and steep braking periods, which offer ample opportunities to recover some energy through braking. On the other hand, the HWFET cycle features more stable speeds and only limited braking times. Consequently, the battery recuperates more energy through regenerative braking during a UDDS cycle than during a HWFET cycle.

Figure 92 shows the strong relationship between vehicle light weighting and electrical consumption.

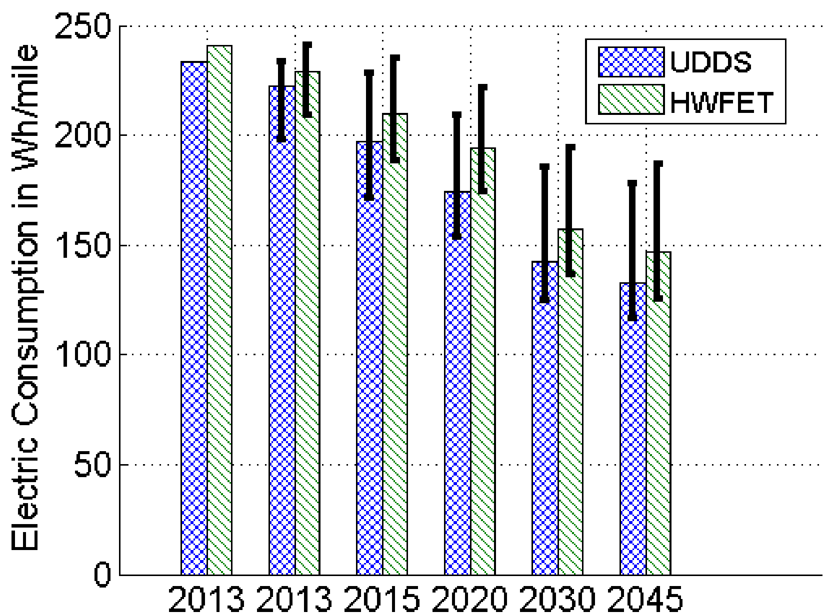


Figure 91 - Electric consumption by midsize BEV100 operating on UDDS and HWFET cycles

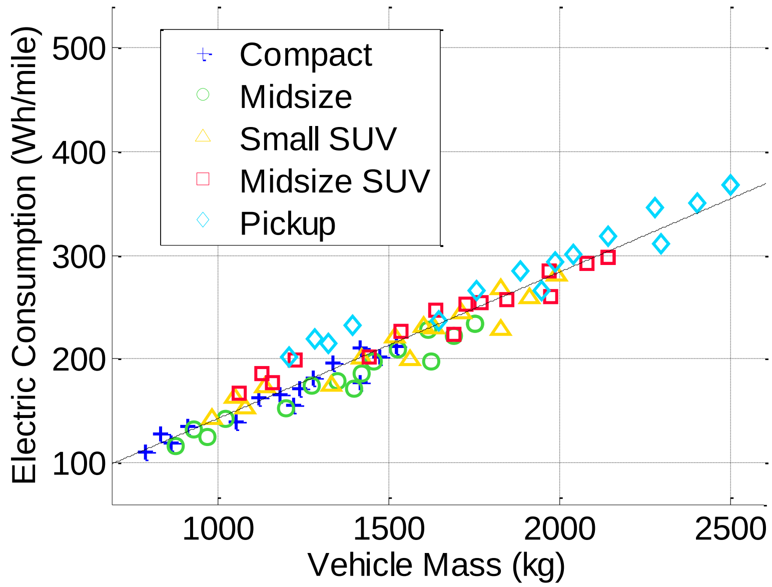


Figure 92 - Electric consumption by EVs

8.2. EVOLUTION OF HEV ENGINES

8.2.1. HEV VERSUS CONVENTIONAL ENGINE

The comparison between power-split HEVs and conventional gasoline vehicles (same year, same case) in Figure 93 shows that the ratios stay fairly constant for until 2020. Indeed, the power-split midsize vehicle consumes between 25% and 45% less fuel than the conventional gasoline vehicle. After 2030, the introduction of micro hybrid vehicles advantage conventional vehicles (becoming start/stop systems) over HEVs. It would be interesting to study the same kinds of ratios, but compare fuel to fuel. This would again demonstrate which fuel would be most advantageous in terms of reduced consumption, in the transition from a conventional to a power-split HEV powertrain.

In Figure 94, the reference considered is the vehicle from the same-year and same-fuel conventional vehicle.

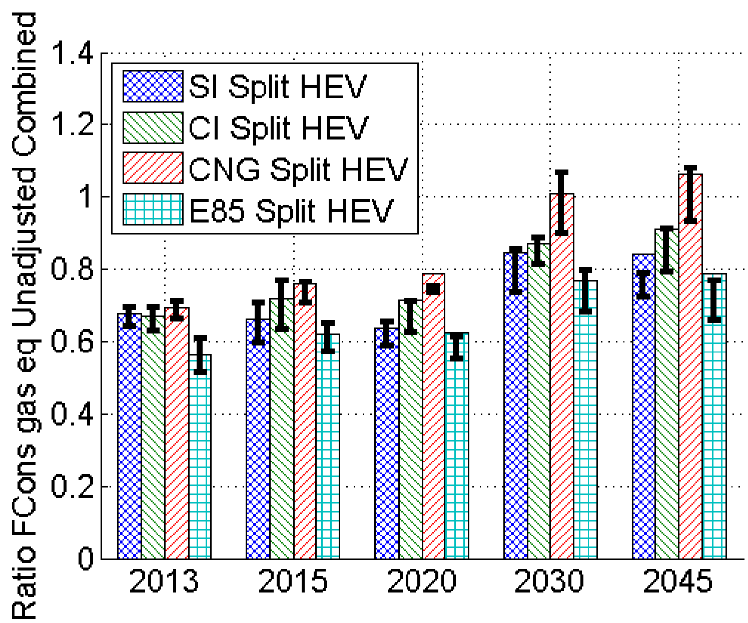


Figure 93 - Gasoline-equivalent fuel consumption for midsize power-split HEVs, compared with the same-year, same-case conventional gasoline vehicle

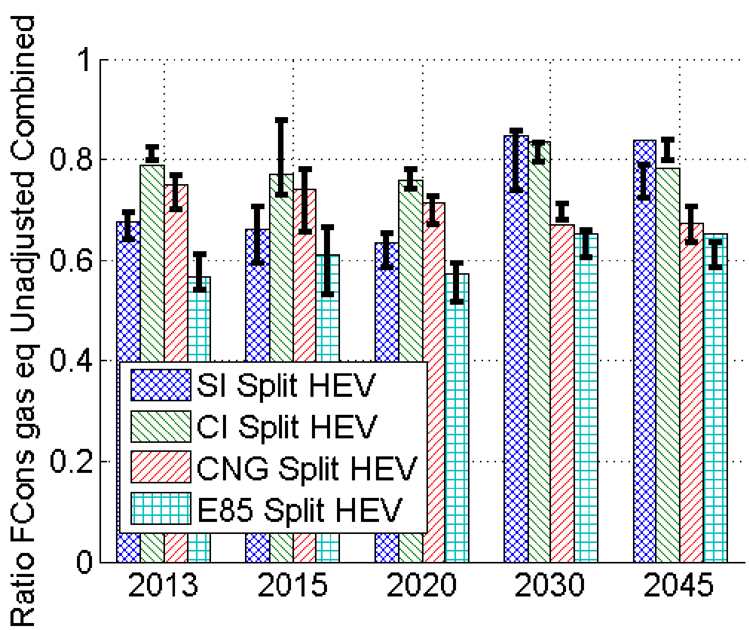


Figure 94 - Gasoline-equivalent fuel consumption for midsize power-split HEVs, compared with same-fuel, same-year conventional midsize vehicle

8.2.2. ENGINE HEV VERSUS FUEL-CELL HEV

The fuel-consumption ratios for all types of power-split HEVs versus fuel-cell HEVs (Figure 95) are higher than 1, showing that fuel-cell technology offers consistently lower fuel consumption than power-split HEV technology. However, the ratios vary over time, and it is pertinent to study the evolution for each fuel. In the reference case, this vehicle consumes nearly 50% more fuel than a fuel-cell HEV; in 2045, however, this difference is reduced to the 20% to 25% range.

Ethanol, diesel, and gasoline power-split vehicles show similar trends. The ratios for these fuels increase from the reference case to 2030 before decreasing in 2045. In contrast, CNG vehicles show a constant increase and reach a 60% increase in 2045.

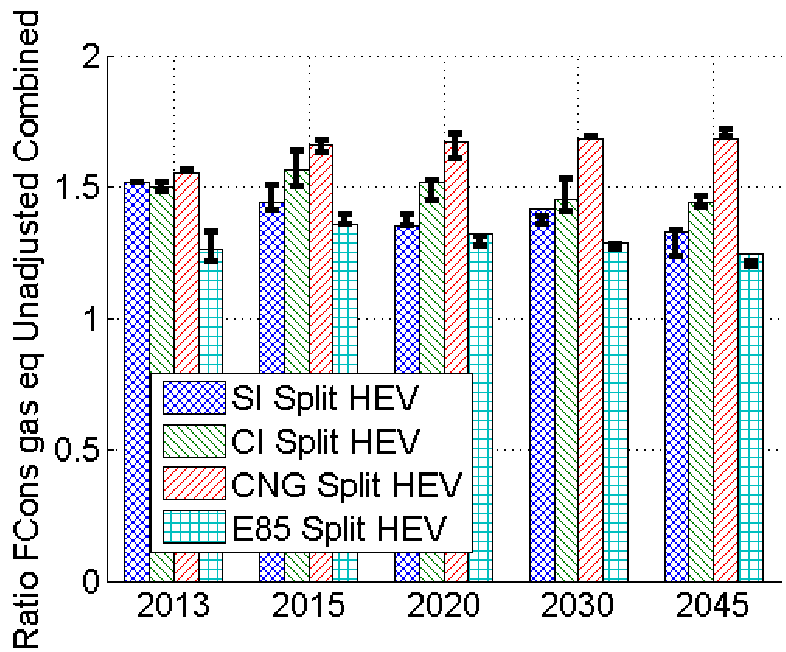


Figure 95 - Gasoline-equivalent fuel consumption for midsize power-split HEVs compared with same-year, same-case midsize fuel-cell HEV

8.3. EVOLUTION OF HYDROGEN-FUELED VEHICLES

8.3.1. FUEL-CELL HEV VERSUS GASOLINE ENGINE

In the reference case, the fuel-cell HEVs consume about 45% less fuel than conventional gasoline vehicles. This difference in fuel consumption increases to the 55% to 65% range in 2045 (Figure 96), indicating that the gasoline conventional vehicle will not improve its fuel consumption as fast as the fuel-cell HEV.

In contrast, Figure 97 shows that in the reference case, fuel-cell HEVs consume about 36% less fuel than gasoline HEVs. This difference in fuel consumption increases in the next two timeframes to reach 55% to 60% in 2045.

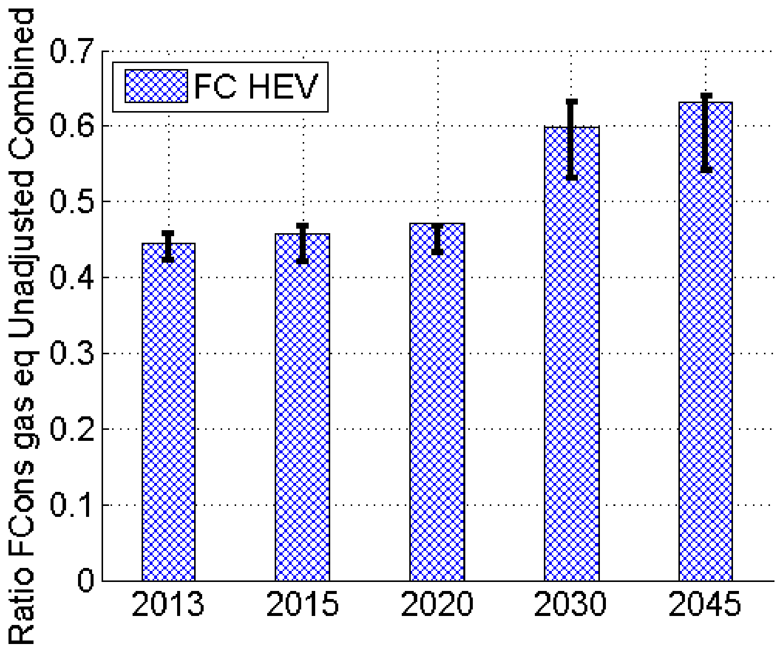


Figure 96 - Gasoline-equivalent fuel consumption for midsize fuel-cell HEV compared with same-year, same-case midsize gasoline

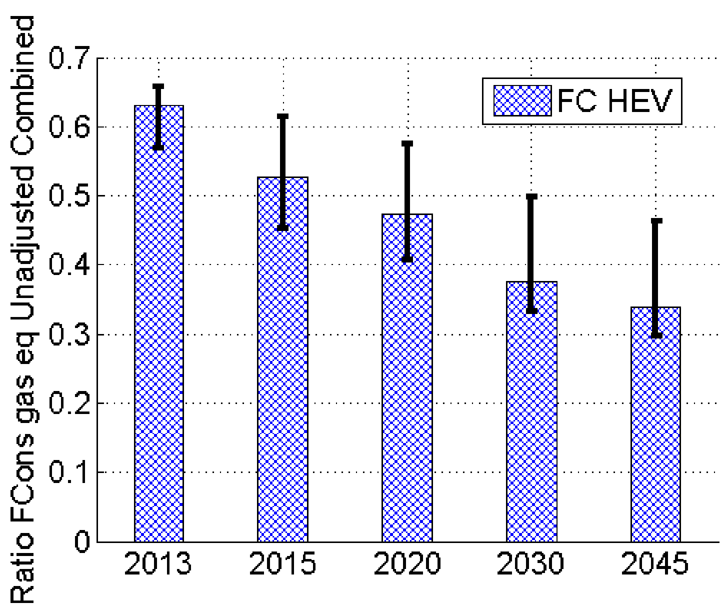


Figure 97 - Gasoline-equivalent fuel consumption for midsize fuel-cell HEV compared with the midsize gasoline split-HEV reference case

9. VEHICLE FUEL CONSUMPTION VERSUS MANUFACTURING COST RESULTS

All costs are manufacturing costs.

9.1. EVOLUTION OF SPECIFIC POWERTRAIN CONFIGURATIONS

9.1.1. CONVENTIONAL

Figure 98 shows manufacturing costs for conventional midsize vehicles. All the prices of vehicles increase from 2013 to 2045. The increase is due to several factors, including lightweighting (the decrease in vehicle body mass by 2045 entails cost increases, due to the use of aluminum or carbon fiber) and advanced component technologies such as direct injection.

Figure 99 shows the manufacturing cost of conventional midsize diesel, CNG, and ethanol vehicles compared with same-year conventional midsize gasoline vehicles.

9.1.2. ENGINE HEVS

Figure 100 shows the vehicle manufacturing costs for the power-split HEVs. The gasoline power-split HEV is generally the cheapest vehicle among all the HEVs. Figure 101 shows that overall, the diesel HEV is between 15% and 20% more expensive than the gasoline HEV. This difference, however, tends to decrease after 2013. From 2013 on, the vehicles cost ratio decreases, reaching almost 1 in 2045.

9.1.3. ENGINE PHEVS

Figure 102 shows the manufacturing cost evolution of PHEVs with different fuels. The overall trend is the same for all fuels; only the actual costs vary. PHEV40 costs show a sharp decrease over time, whereas PHEV10s show a very slight decrease over time. This observation can be explained by improvements in batteries over time.

Figure 103 shows the manufacturing cost of PHEVs compared with gasoline HEVs. Again, the PHEVs become more cost-competitive over time because of improvements in batteries.

9.1.4. FUEL-CELL VEHICLES

Fuel-cell vehicle manufacturing costs (Figure 104) show a pattern similar to that of previously described gasoline-vehicle manufacturing cost. Indeed, as time goes on, the different vehicles' manufacturing costs become closer and closer to each other. In 2013, a fuel-cell PHEV40 is approximately 45% more expensive than a fuel-cell HEV, whereas it is less expensive in 2045. Finally, it is interesting to note that in 2045, the fuel-cell vehicle manufacturing costs are under $20,000 for all the average and high cases.

9.1.5. ELECTRIC VEHICLES

As shown in Figure 105, improvements in battery costs and lightweighting affect EV costs, which are expected to decrease by a factor greater than 2.

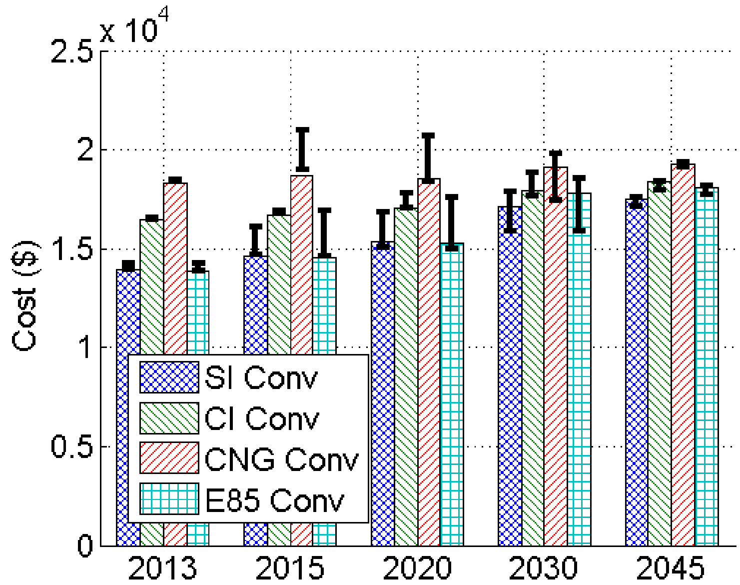


Figure 98 - Manufacturing cost of conventional vehicles

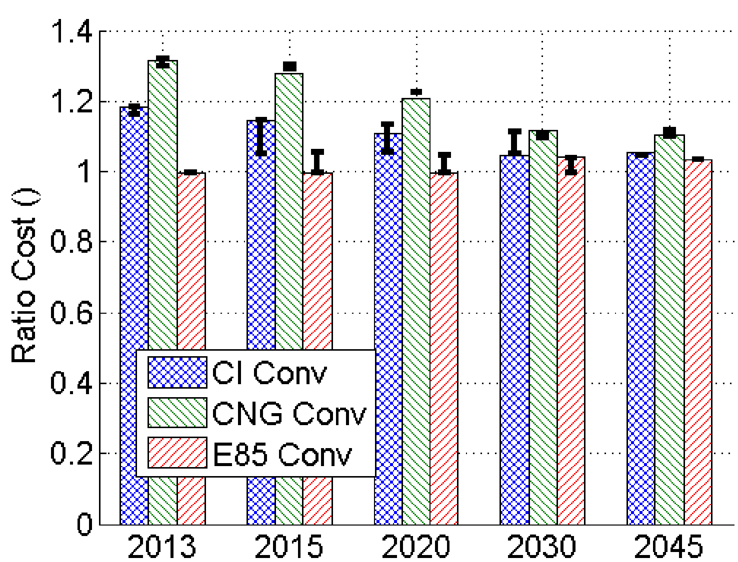


Figure 99 - Manufacturing costs of diesel, CNG, and ethanol conventional midsize cars compared with same-year gasoline conventional midsize car

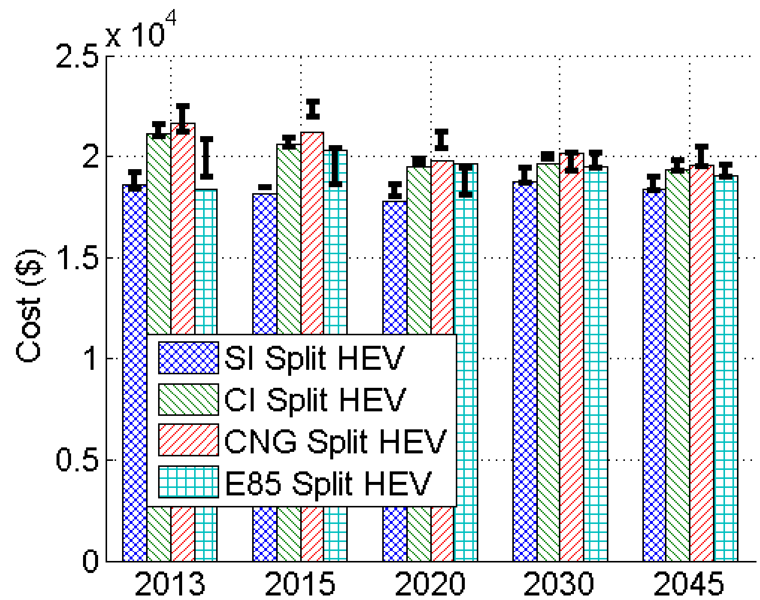


Figure 100 - Manufacturing costs of midsize HEVs

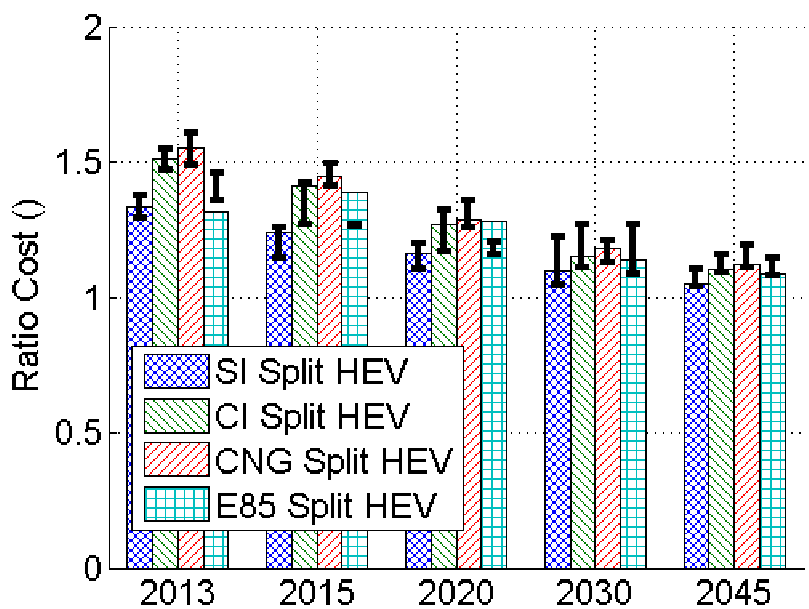


Figure 101 - Manufacturing costs of midsize HEVs compared with same-year conventional gasoline-powered vehicles

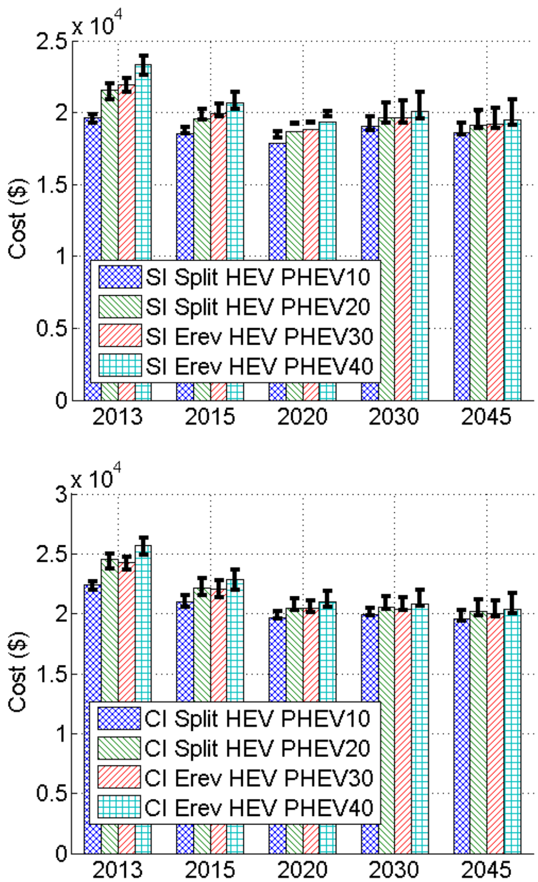


Figure 102 - Manufacturing cost of PHEV for all fuels

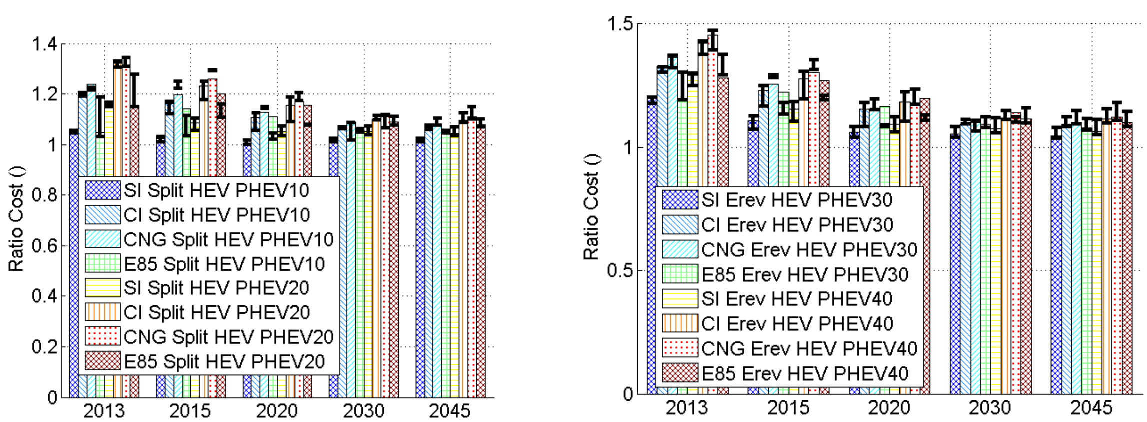


Figure 103 - Manufacturing costs of midsize PHEVs compared with same-year gasoline-powered HEV

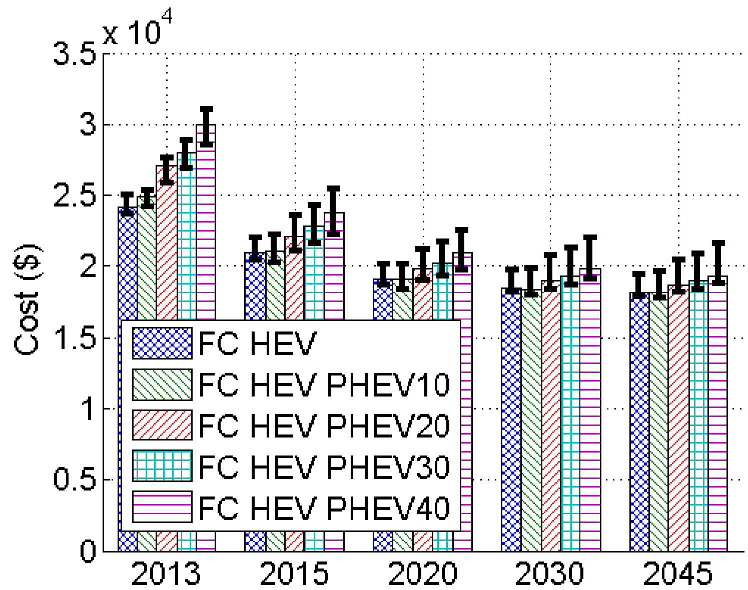


Figure 104 - Manufacturing costs of midsize fuel-cell vehicles

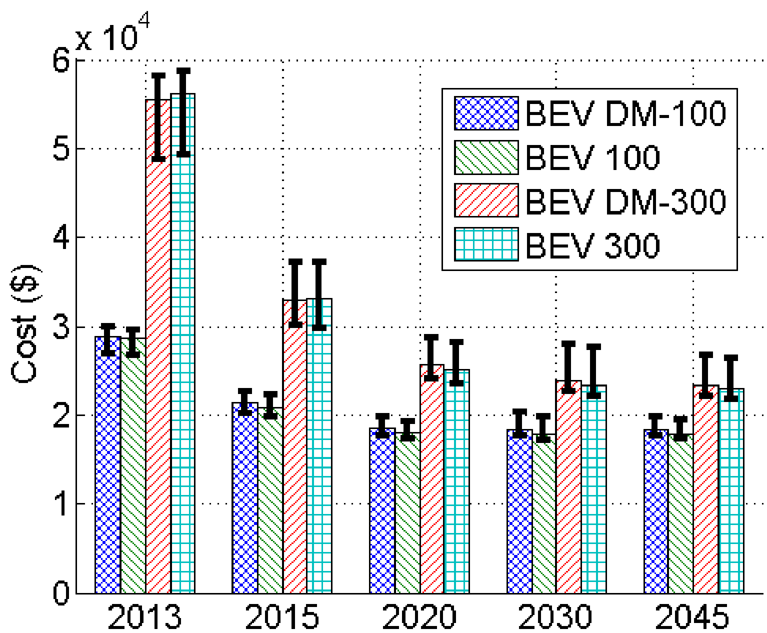


Figure 105 - Manufacturing costs for midsize EVs

9.2. POWERTRAIN COMPARISON

Figure 106 shows the manufacturing costs for all the gasoline-powertrain vehicles (conventional, power-split HEV, and power-split PHEVs). The manufacturing costs tend to get closer to each other as time goes on. For example, in 2016, the power-split HEV is 35% more expensive than the conventional vehicle, and the PHEV40 is 78% more expensive than the conventional vehicle. However, in 2045, the situation dramatically changes; only a 3% to 6% difference in manufacturing cost is observed for the power-split HEV, and 11% to 17% for the power-split PHEV40.

Whereas the conventional-vehicle manufacturing cost increases slightly over time, the opposite pattern is observed for power-split vehicles. The higher the AER, the greater the manufacturing cost reduction over time.

Figure 107 shows the relative manufacturing costs of CNG vehicles and conventional gasoline vehicles. While CNG engines will remain more expensive, the technology will become more cost-competitive over time.

Figure 108 shows the manufacturing cost ratio between fuel-cell and conventional gasoline vehicles.

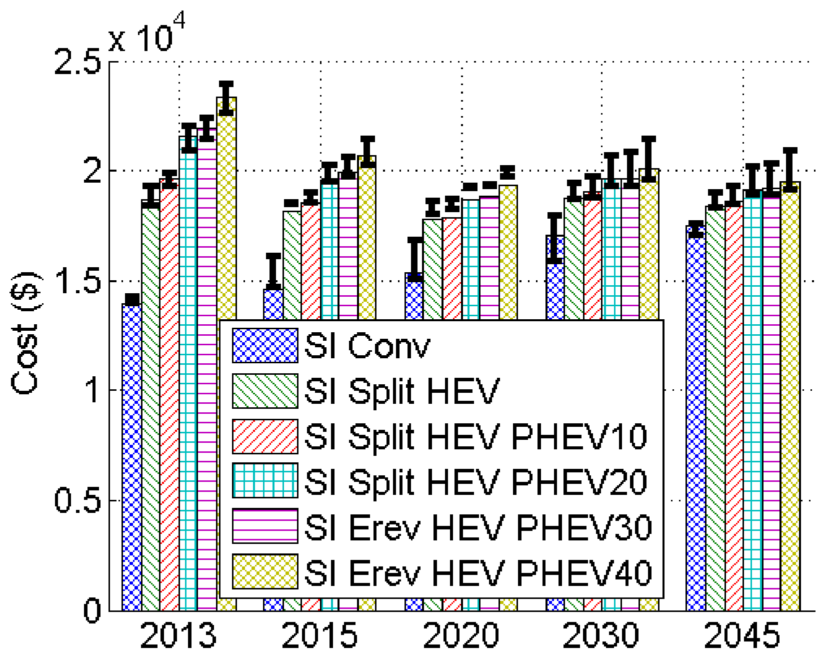


Figure 106 - Manufacturing costs of midsize gasoline-powered vehicles

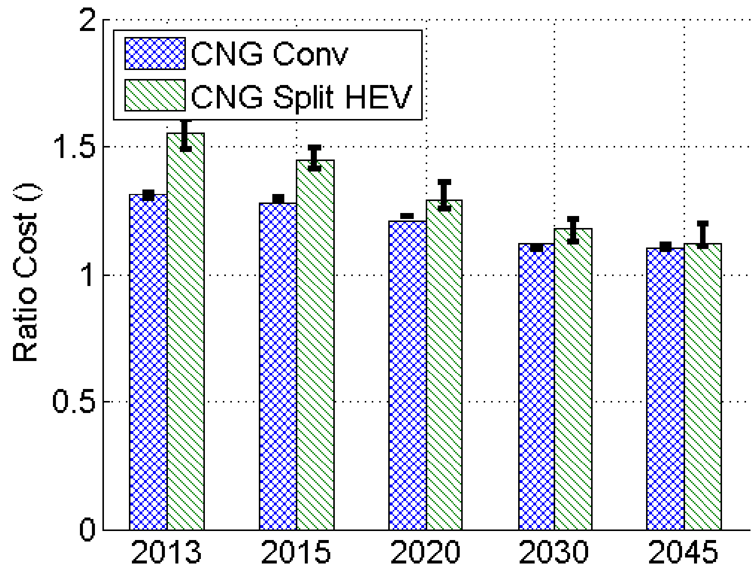


Figure 107 - Manufacturing costs of midsize CNG ICE vehicles compared with same-year conventional gasoline vehicles

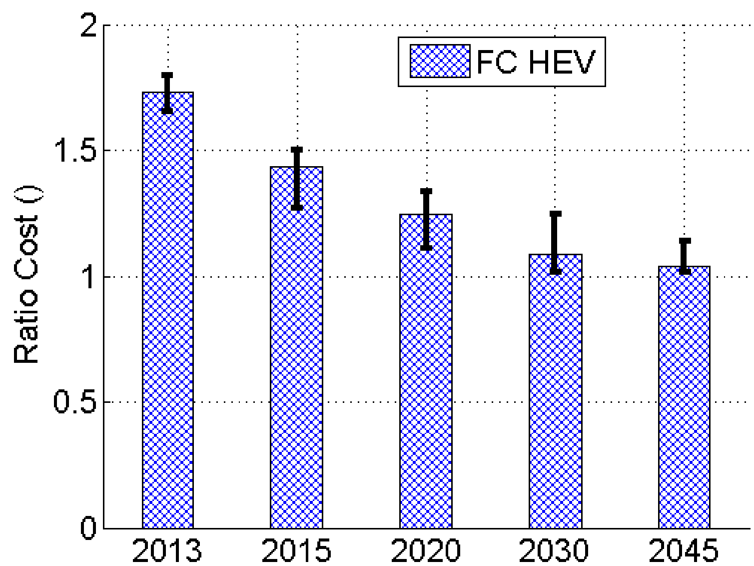


Figure 108 - Manufacturing cost of midsize fuel-cell HEV compared with same-year conventional gasoline vehicle

10. TRADE-OFF BETWEEN VEHICLE FUEL CONSUMPTION AND MANUFACTURING COST

All costs are manufacturing costs.

10.1. CONVENTIONAL VEHICLES

Figure 109 shows that diesel vehicles remain more expensive relative to other conventional vehicles over time, with no advantage in fuel consumption.

10.2. HEVS

Figure 110 shows similar trends for HEVs, independently of ICE technology. The overall trend is decreasing, which means lower fuel consumption and lower cost. Gasoline and ethanol HEVs offer the best trade-offs over time, with the diesel HEV becoming competitive in the 2045 timeframe.

10.3. PHEVS

Figures 111 and 112 show, respectively, that PHEV10 and PHEV40 vehicles offer less future benefit than conventional vehicles, although the overall trend is promising.

10.4. FUEL-CELL AND OTHER HYDROGEN-FUELED VEHICLES

Figure 113 shows the trade-offs of incremental manufacturing cost versus fuel consumption for fuel-cell HEVs and PHEVs compared with the reference conventional gasoline vehicles. For the PHEVs, we found a diminishing return on investment, since little fuel-efficiency gain is achieved for the higher AER despite a higher manufacturing cost. Overall, all configurations trend toward good fuel efficiency at a low manufacturing cost.

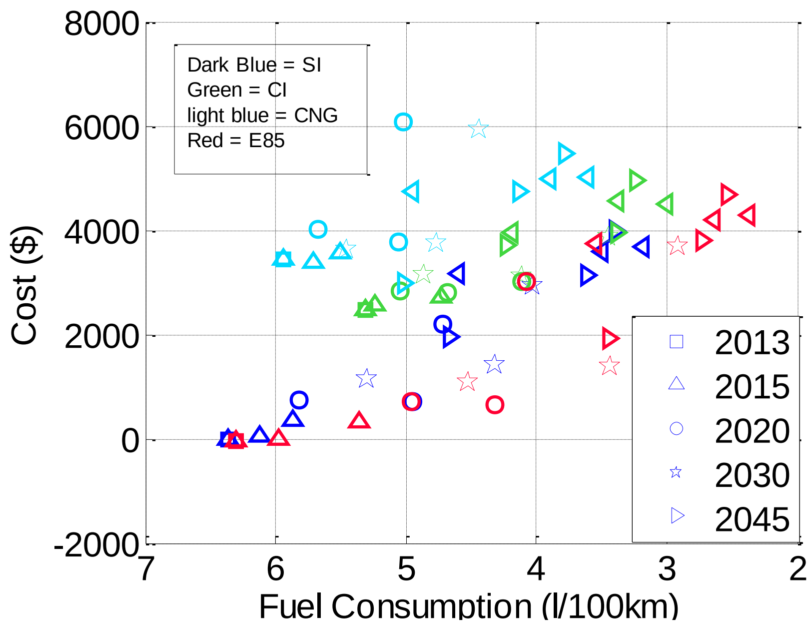


Figure 109 - Incremental manufacturing cost (in comparison with the reference conventional gasoline vehicle manufacturing cost) as a function of fuel consumption for midsize conventional vehicles

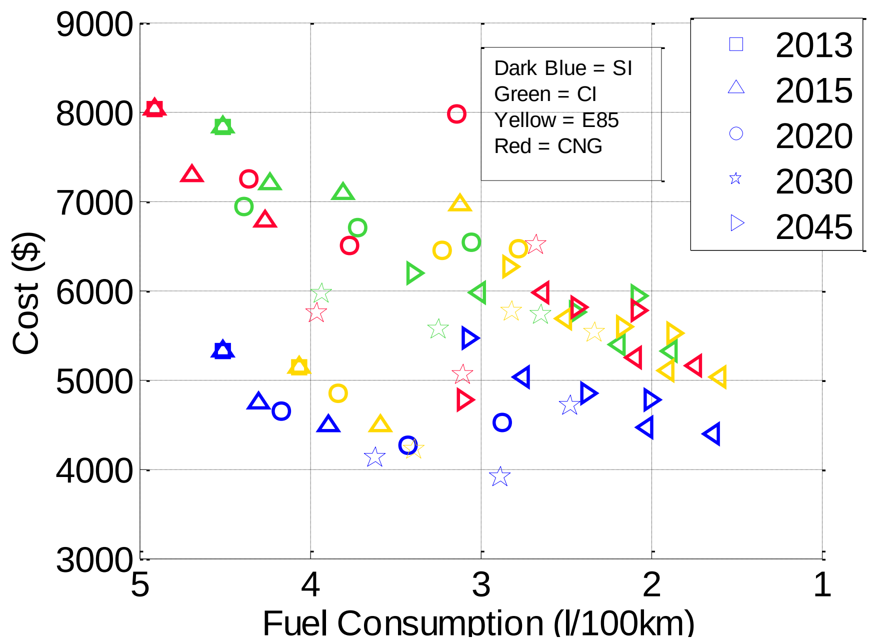


Figure 110 - Incremental manufacturing cost (in comparison with the reference conventional gasoline vehicle manufacturing cost) as a function of fuel consumption for midsize HEVs

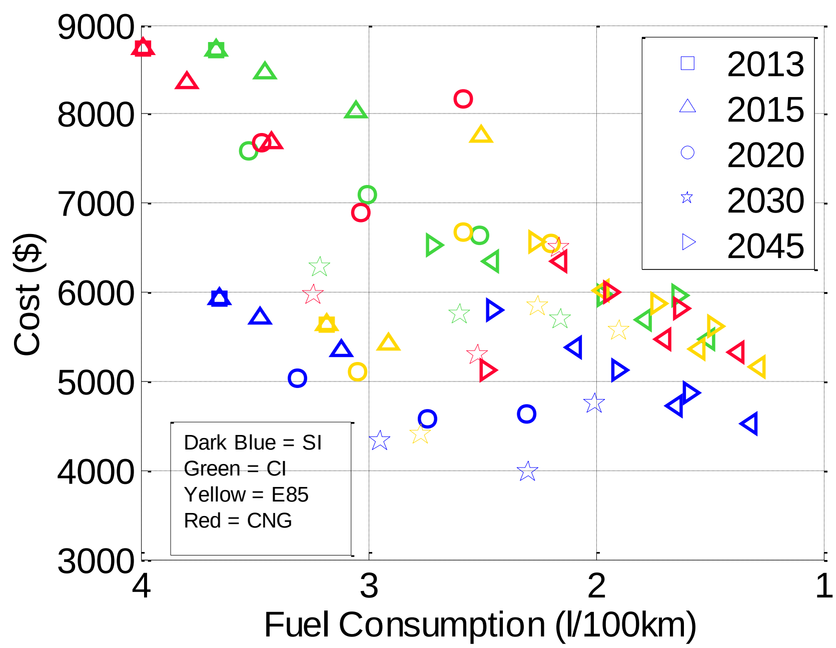


Figure 111 - Incremental manufacturing cost (in comparison with the reference conventional gasoline vehicle manufacturing cost) as a function of fuel consumption for PHEV10 vehicles

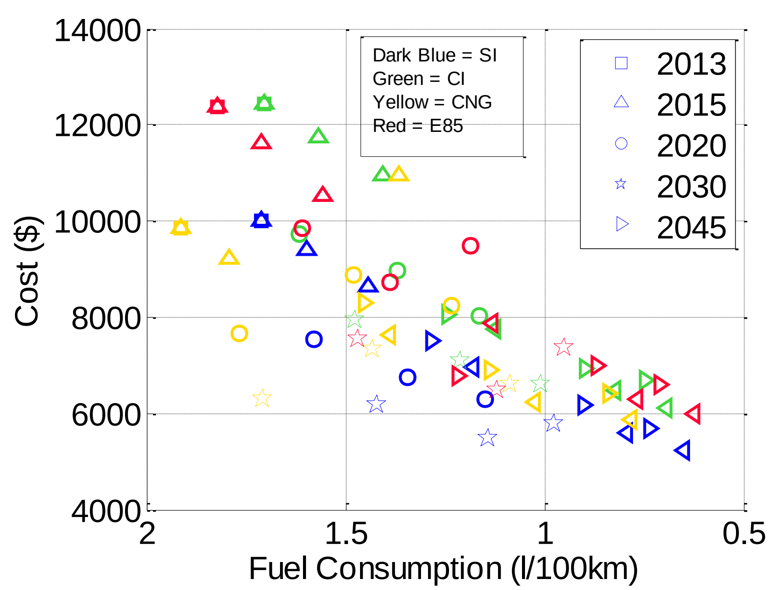


Figure 112 - Incremental manufacturing cost (in comparison to the reference conventional gasoline vehicle manufacturing cost) as a function of fuel consumption for PHEV40 vehicles

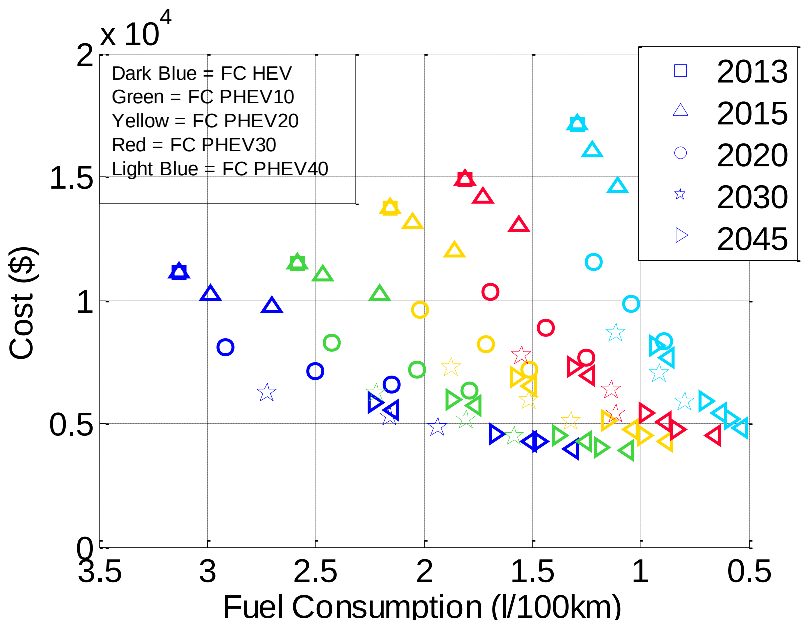


Figure 113 - Incremental manufacturing cost (in comparison with the reference conventional gasoline vehicle manufacturing cost) as a function of fuel consumption for fuel-cell vehicles

10.5. ALL POWERTRAINS

Figure 114 shows the trade-offs between fuel consumption and increased manufacturing costs for all powertrains and fuels compared with the conventional gasoline reference. Overall, the vehicles on the bottom right would provide the best fuel consumption for the least additional cost. All years, all cases, and all fuels are presented.

Figure 115 shows a comparison of all the powertrains, considering gasoline fuel only. The main conclusion to be drawn from Figure 115 is that conventional vehicles are more likely to improve in fuel efficiency than in cost, whereas the higher the electrification level, the more the improvement focuses on cost.

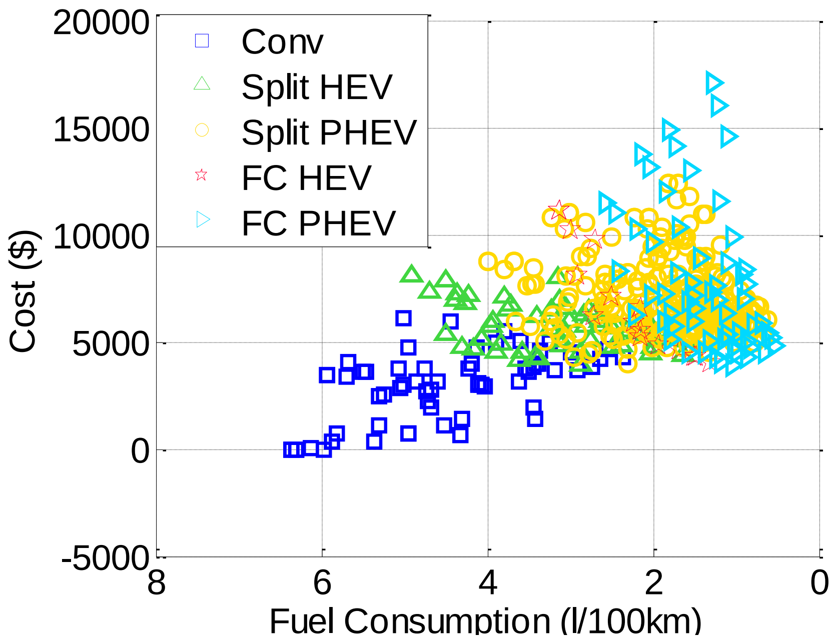


Figure 114 - Incremental manufacturing cost (in comparison with the gasoline conventional reference vehicle) as a function of fuel consumption for all powertrains

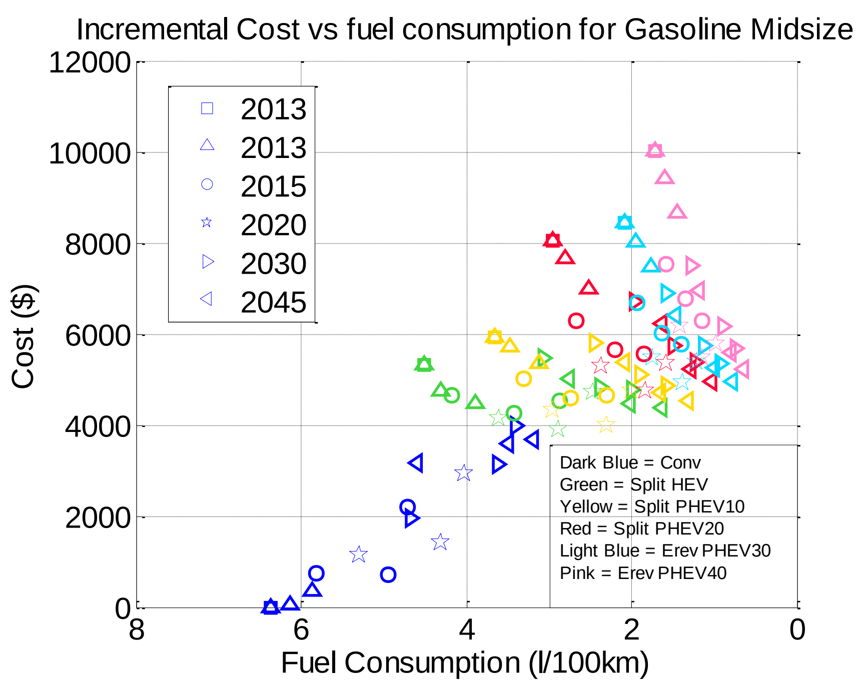


Figure 115 - Incremental manufacturing cost (in comparison with the reference conventional gasoline vehicle manufacturing cost) as a function of fuel consumption for gasoline vehicles

11. REFERENCES

Argonne National Laboratory (2011a). *Autonomie.* http://www.autonomie.net/.

Argonne National Laboratory (2011b). *Autonomie/Papers.* http://www.autonomie.net/overview/papers_software.html.

Autoblog (2008). By the Numbers May 2008: F-150 Falls Edition. http://www.autoblog.com/2008/06/03/by-the-numbers-may-2008-f-150-falls-edition.

Bandel, W. (2006). *The Turbocharged GDI Engine: Boosted Synergies for High Fuel Economy plus Ultra-Low Emissions.* Society of Automotive Engineers (SAE) paper 2006-01-1266, presented at the SAE World Congress & Exhibition, Detroit, MI, April.

Bohn, T.A. (2005). *Implementation of a Non-Intrusive In-Vehicle Engine Torque Sensor for Benchmarking the Toyota Prius HEV.* SAE paper 2005-01-1046, presented at the SAE World Congress & Exhibition, Detroit, MI, April.

Cao, Q.P. (2007). *PHEV Hymotion Prius Model Validation and Control Improvements.* Presented at the the 23rd International Electric Vehicle Symposium (EVS23), Anaheim, CA, Dec.

Ciatti, S., and Subramanian, S. (2010). *An Experimental Investigation of Low Octane Gasoline in Diesel Engines*. http://www1.eere.energy.gov/vehiclesandfuels/pdfs/deer_2010/wednesday/presentations/deer10_ciatti.pdf.

CSI (Civil Society Institute) (2007). *CSI/40mpg.org: "Fuel-Efficient Car Gap" Growing as U.S. Falls to Two 40mpg+ Vehicles, While Number of Gas-Sipping Cars Unavailable in U.S. Rises to Well Over 100.* http://www.civilsocietyinstitute.org/media/pdfs/021407_CSI_40mpg_fuel_efficiency_news_release.pdf.

Delorme, A., Rousseau, A., and Pagerit, R. (2008). *Fuel Economy Potential of Advanced Configurations from 2010 to 2045.* Presented at the IFP HEV Conference, Paris, Nov.

DOE (U.S. Department of Energy) (n.d.[a]). *Energy Efficiency and Renewable Energy/Planning, Budget, & Analysis/Data & Analysis.* http://www1.eere.energy.gov/ba/pba/program_benefits.html.

DOE (n.d.[b]). *Vehicle Technologies Program.* http://www1.eere.energy.gov/vehiclesandfuels/resources/fcvt_software.html.

DOE (2007). *Plug-In Hybrid Electric Vehicle R&D Plan, Working Draft, June 2007.* http://www1.eere.energy.gov/vehiclesandfuels/pdfs/program/phev_rd_plan_june_2007.pdf

DOE (2010). *The Recovery Act: Transforming America's Transportation Sector—Batteries and Electric Vehicles*, July 14.

EIA_1. Energy Information Administration, International Energy Statistics, June 2015

EIA_2. U.S. Department of Energy, Energy Information Administration, Monthly Energy Review, Washington, DC, May 2015, Tables 3.3c and 3.3d

EIA_3. U.S. Department of Energy, Energy Information Administration, Monthly Energy Review, June 2015, Tables 2.2–2.6

EIA4. https://www.eia.gov/dnav/pet/pet_pri_spt_s1_d.htm

Elgowainy, A., Burnham, A., Wang, M., Molburg, J., and Rousseau, A. (2009). *Well-To-Wheels Energy Use and Greenhouse Gas Emissions of Plug-in Hybrid Electric Vehicles.* SAE paper 2009-01-1309, presented at the SAE World Congress & Exhibition, Detroit, MI, April.

EPA (U.S. Environmental Protection Agency) (n.d.). *Fuel Economy.* http://www.epa.gov/fueleconomy/regulations.htm.

EPA (2010). *Light Duty Automotive Technology, Carbon Dioxide Emissions and Fuel Economy Trends: 1975 through 2010*. EPA-420-R10-023, Nov.

EPA 2013, Light-Duty Automotive Technology, Carbon Dioxide Emissions, and Fuel Economy Trends: 1975 Through 2013

Faron, G., Pagerit, S., and Rousseau, A. (2009). *Evaluation of PHEVs Fuel Efficiency and Cost Using Monte Carlo Analysis.* Presented at the 24th International Electric Vehicle Symposium (EVS24), Stavanger, Norway, May 2009. http://www.transportation.anl.gov/pdfs/HV/565.pdf.

Fellah, M., Singh, G., Rousseau, A., Pagerit, S., Nam, E., and Hoffman, G. (2009). *Impact of Real-World Drive Cycles on PHEV Battery Requirements.* SAE paper 2009-01-1383, presented at the SAE World Congress & Exhibition, Detroit, MI, April. http://www.autonomie.net/docs/6%20-%20Papers/HEVs%20&%20PHEVs/Component%20Requirements/impact_of_real_world_drive_cycles.pdf.

Freyermuth, V., Fallas, E., and Rousseau, A. (2008). *Comparison of Powertrain Configuration for Plug-in HEVs from a Fuel Economy Perspective.* SAE paper 2008-01-0461, presented at the SAE World Congress & Exhibition, Detroit, MI, April. (Selected for SAE *International Journal of Engines*.) http://papers.sae.org/2008-01-0461/.

Grewe, T.M., Conlon, B.M., and Holmes, A.G. (2007). *Defining the General Motors 2-Mode Hybrid Transmission.* SAE paper 2007-01-0273, presented at the SAE World Congress & Exhibition, Detroit, MI, April.

Henrion, M. (2008). *Guide to Estimating Unbiased Probability Distributions for Energy R&D Results.* DOE Risk Analysis Group.

Howell, D., "U.S. Battery R&D Progress and Plans", DOE Annual Merit Review, June 2013

IEA (International Energy Agency) (2010). *2010 Key World Energy Statistics*. http://www.iea.org/textbase/nppdf/free/2010/key_stats_2010.pdf.

Karbowski, D., Rousseau, A., Pagerit, S., and Sharer, P. (2006). *Plug-in Vehicle Control Strategy: From Global Optimization to Real-Time Application.* Presented at the 22nd International Electric Vehicle Symposium (EVS22), Yokohama, Japan, Oct. http://www.transportation.anl.gov/pdfs/HV/435.pdf.

Karbowski, D., Haliburton, C., and Rousseau, A. (2007). *Impact of Component Size on Plug-In Hybrid Vehicle Energy Consumption Using Global Optimization.* Presented at the 23rd International Electric Vehicle Symposium (EVS23), Anaheim, CA, Dec. http://www.transportation.anl.gov/pdfs/HV/460.pdf.

Karbowski, D., Pagerit, S., Kwon, J., Rousseau, A., and Freiherr von Pechmann, K-F. (2009). *Fair Comparison of Powertrain Configurations for Plug-In Hybrid Operation Using Global Optimization.* SAE paper 2009-01-1334, presented at the SAE World Congress & Exhibition, Detroit, MI, April. http://papers.sae.org/2009-01-1334/.

Karbowski, D., Kwon, J., Kim, N., and Rousseau, A. (2010). *Instantaneously Optimized Controller for a Multimode Hybrid Electric Vehicle.* SAE paper 2010-01-0816, presented at the SAE World Congress & Exhibition, Detroit, MI, April. http://papers.sae.org/2010-01-0816/.

Kim, N., Carlson, R., Jehlik, F., and Rousseau, A. (2009). *Tahoe HEV Model Development in PSAT.* SAE paper 2009-01-1307, presented at the SAE World Congress & Exhibition, Detroit, MI, April. http://papers.sae.org/2009-01-1307.

Kim, N., Kwon, J., and Rousseau, A. (2010). *Trade-off Between Multi-mode Powertrain Complexity and Fuel Consumption.* Presented at the 25th International Electric Vehicle Symposium (EVS25), Shenzhen, China, November 5–9, 2010. http://www.autonomie.net/docs/6%20-%20Papers/HEVs%20&%20PHEVs/Powertrain%20Configurations/trade-off_between_multimode.pdf

Kromer, M.A., and Heywood, J.B. (2008). *A Comparative Assessment of Electric Propulsion Systems in the 2030 US Light-Duty Vehicle Fleet.* SAE paper 2008-01-0459, presented at the SAE World Congress & Exhibition, Detroit, MI, April.

Mathworks (n.d.). *Argonne National Laboratory Develops Powertrain System Analysis Toolkit with MathWorks™ Tools.* http://www.mathworks.com/company/user_stories/userstory45700.html.

Mathworks (2007). *Matlab Release 4.7, User's Guide.*

Moawad and Rousseau, 2012, "Impact of Electric Drive Vehicle Technologies on Fuel Efficiency", June 2012, ANL/ESD/12-7

Morrow, K., Karner, D., and Francfort, J. (2008). *Plug-in Hybrid Electric Vehicle Charging Infrastructure Review.* Report No. INL/EXT-08-15058. http://avt.inl.gov/pdf/phev/phevInfrastructureReport08.pdf.

National Research Council (2011). *Assessment of Fuel Economy Technologies for Light-Duty Vehicles.* Washington, D.C.: The National Academies Press (in press).

Nelson, P., Amine, K., Rousseau, A., and Yomoto, H. (2007). *Advanced Lithium-Ion Batteries for Plug-in Hybrid-Electric Vehicles.* Presented at the 23rd International Electric Vehicle Symposium (EVS23), Anaheim, CA, Dec. http://www.transportation.anl.gov/pdfs/HV/461.pdf.

Pagerit, S. (2007). *Using Matlab Distributed Computing for Vehicle Simulations.*

Pagerit, S., Rousseau, A., and Sharer, P. (2005). *Global Optimization to Real Time Control of HEV Power Flow: Example of a Fuel Cell Hybrid Vehicle.* Presented at the 21st International Electric Vehicle Symposium (EVS21), Monaco, April 2005. http://www.transportation.anl.gov/pdfs/HV/441.pdf.

Pagerit, S., Sharer, P., and Rousseau, A. (2006). *Fuel Economy Sensitivity to Vehicle Mass for Advanced Vehicle Powertrains.* SAE paper 2006-01-0665, presented at the SAE World Congress & Exhibition, Detroit, MI, April.

Pasquier, M., Duoba, M., and Rousseau, A. (2001). *Validating Simulation Tools for Vehicle System Studies Using Advanced Control and Testing Procedure.* Presented at the 18th International Electric Vehicle Symposium (EVS18), Berlin, Germany, October 20–24. http://www.autonomie.net/docs/6%20-%20Papers/Validation/validating_simulation_tools.pdf.

Rousseau, A. (n.d.). *What Can Autonomie Do for You?* http://www.autonomie.net/docs/5%20-%20Presentations/Software/what_can_autonomie.pdf.

Rousseau, A., (2000). *Simulation and Validation of Hybrid Electric Vehicles Using AUTONOMIE.* Presented at the 3rd Global Powertrain Congress, Detroit, MI, June 6–8.

Rousseau, A., and Moawad, A. (2010). *Impact of Control Strategies on Fuel Efficiency of Different PHEVs Using Real World Driving Conditions.* Presented at IAMF 2010, Geneva, Switzerland, March 9–10. http://www.autonomie.net/docs/6%20-%20Papers/HEVs%20&%20PHEVs/Control%20Strategy/impact_of_control_strategies.pdf.

Rousseau, A., Sharer, P., and Ahluwalia, R. (2004). *Energy Storage Requirements for Fuel Cell Vehicles.* SAE paper 2004-01-1302, presented at the SAE World Congress & Exhibition, Detroit, MI, March. http://www.autonomie.net/docs/6%20-%20Papers/Hydrogen_fueled/energy_storage_requirements.pdf.

Rousseau, A., Sharer, P., and Pagerit, S. (2005). *Trade-off between Fuel Economy and Cost for Advanced Vehicle Configurations.* Presented at the 20th International Electric Vehicle Symposium (EVS20), Monaco, April 2005. http://www.transportation.anl.gov/pdfs/HV/340.pdf.

Rousseau, A., Kwon, J., Sharer, P., Pagerit, S., and Duoba, M. (2006). *Integrating Data, Performing Quality Assurance, and Validating the Vehicle Model for the 2004 Prius Using AUTONOMIE.* SAE paper 2006-01-0667, presented at the SAE World Congress & Exhibition, Detroit, MI, April. http://papers.sae.org/2006-01-0667.

Rousseau, A., Pagerit, S., and Gao, D.W. (2008). *Plug-in Hybrid Electric Vehicle Control Strategy Parameter Optimization.* Journal of Asian Electric Vehicles, **6**(2), pp. 1125–1133.

Sharer, P., Rousseau, A., Pagerit, S., and Nelson, P. (2007). *Midsize and SUV Vehicle Simulation Results for Plug-in HEV Component Requirements.* SAE paper 2007-01-0295, presented at the SAE World Congress & Exhibition, Detroit, MI, April. http://www.autonomie.net/docs/6%20-%20Papers/HEVs%20&%20PHEVs/Component%20Requirements/midsize_and_suv_vehicle_simulation.pdf.

Sharer, P., Rousseau, A., Karbowski, D., and Pagerit, S. (2008). *Plug-in Hybrid Electric Vehicle Control Strategy: Comparison between EV and Charge-Depleting Options.* SAE paper 2008-01-0460, presented at the SAE World Congress & Exhibition, Detroit, MI, April.

Slezak, L. (2008). *The U.S. Hybrid and Plug-in Hybrid Vehicle Research Program*, presented at the International Conference on Advances in Hybrid Powertrains, Ruell-Malmaison, France, Nov. 25–26.

Tate, E.D., and Savagian, P.J. (2009). *The CO_2 Benefits of Electrification E-REVs, PHEVs and Charging Scenarios.* SAE paper 2009-01-1311, presented at the SAE World Congress & Exhibition, Detroit, MI, April.

USCAR (United States Council for Automotive Reserch, LLC) (2010). *Press Release: USAMP-A/SP-VALIDATION-PROJECT-YIELDS-PASSENGER-COMPARTMENT-MASS-SAVINGS-OF-15-20-PERCENT.* http://www.uscar.org/guest/news/465/Press-Release-USAMP-A-SP-VALIDATION-PROJECT-YIELDS-PASSENGER-COMPARTMENT-MASS-SAVINGS-OF-15-20-PERCENT.

Vehicle Systems Analysis Technical Team (2006). *FreedomCAR and Fuel Partnership.* http://www1.eere.energy.gov/vehiclesandfuels/pdfs/program/vehicle_sys_analysis_team_tech_roadmap.pdf .

Vijayagopal, R., Shidore, N., Halbach, S., Michaels, L., and Rousseau, A. (2010). *Automated Model Based Design Process To Evaluate Advanced Component Technologies.* SAE paper 2010-01-0936, presented at the SAE World Congress & Exhibition, Detroit, MI, April. http://www.autonomie.net/docs/6%20-%20Papers/CIL/automated_model_based_design.pdf.

Wallner, T., and Lohse-Busch, H. (2007). *Performance, Efficiency, and Emissions Evaluation of a Supercharged, Hydrogen-Powered, 4-Cylinder Engine.* SAE paper 2007-01-0016, presented at the SAE Fuels and Emissions Conference, Capetown, South Africa, Jan. http://papers.sae.org/2007-01-0016

Wang, M. (2006). *Projection of Chinese Electric Machine Vehicle Growth, Oil Demand and CO_2 Emissions through 2050.* http://www.transportation.anl.gov/pdfs/TA/398.pdf.

Ward, J. (2010.) *VTP FY12 Goals to Autonomie Crosswalk 20100414.xlsx.*

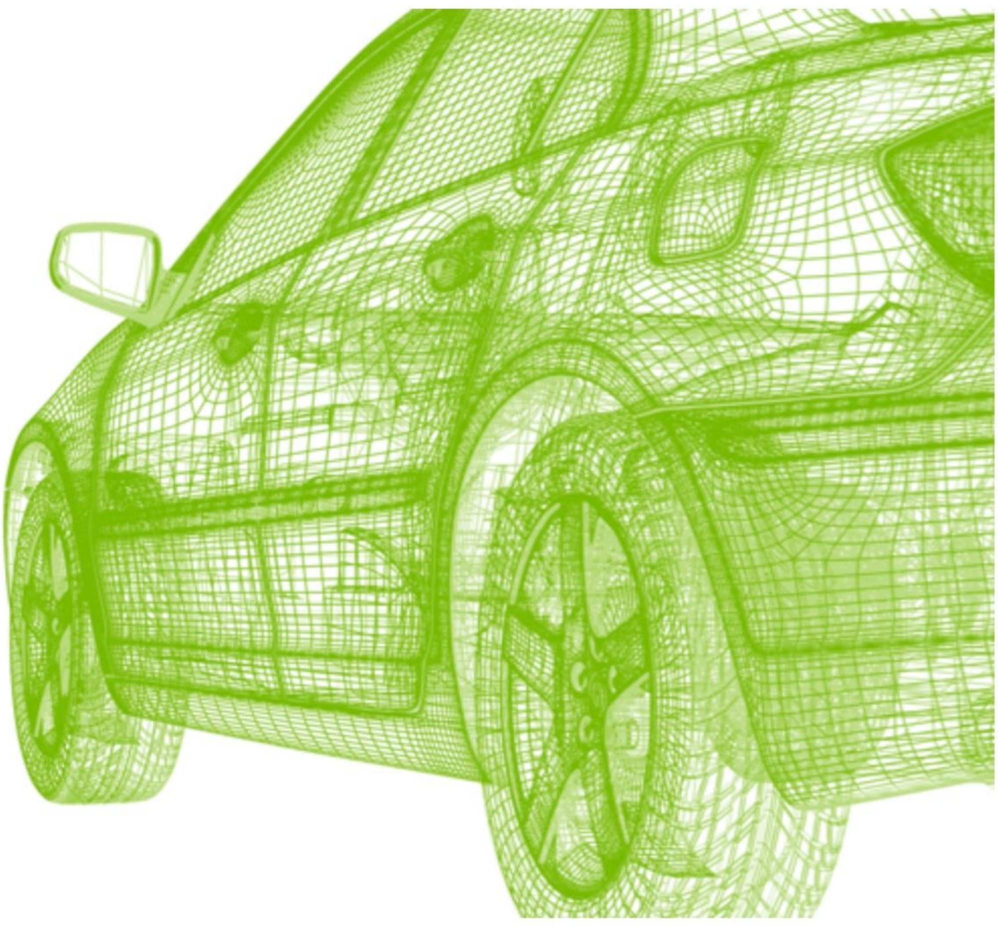
Wu, Y., Wang, M.Q., Dharer, P.B., and Rousseau, A. (2006). *Well-to-Wheels Results of Energy Use, Greenhouse Gas Emissions and Criteria Air Pollutant Emissions of Selected Vehicle/Fuel Systems.* SAE 2006 Transactions (*Journal of Engines*), Paper No. 2006-01-0377. http://www.transportation.anl.gov/pdfs/TA/382.pdf.

Zhou, Yan and Anant Vyas 2013 personal communication:
http://www.transportation.anl.gov/technology_analysis/edrive_vehicle_monthly_sales.html

Argonne NATIONAL LABORATORY

Energy Systems Division
Argonne National Laboratory
9700 South Cass Avenue, Bldg. 362
Argonne, IL 60439-4815

www.anl.gov



U.S. DEPARTMENT OF ENERGY